Section 4. The National Core Network (NCore)

4.1 Background

Air monitoring efforts serve a variety of needs, both national and local. The rationale for even considering national based networks is simply a recognition that a very significant part of any "local" air pollution problem often is associated with some form of long-range transport or part of an extensive region-wide airshed. Similarly, a major component of emissions reduction strategies are based on national programs (e.g., the Federal Motor Vehicle Control Program, Clean Air Act Title IV [acid rain precursors], nitrogen oxide [NOx], SIP calls in the eastern United States, and the recent Clear Skies program. The nature of "national" ambient air quality standards implies an understanding of the cause-effect phenomena between pollutants and adverse health impacts is based on a range of diverse populations and locations throughout the Nation. Numerous national level modeling tools drive a range of air quality prediction and health assessments requiring consistency in measurement approaches.

It is assumed that the need for monitoring to characterize and assess localized air quality issues is comparable to that required for national needs. Therefore, the development of a national network component must allow for needed flexibility to address local issues as well as accommodating emerging technologies and science/policy needs that often are constricted by massive infrastructures. In application, enough overlap exists between national and local design features, such that a network designed for a national purpose more often than not also services a local need. For example, a national speciation trends site is used in concert with other mass and speciation sites for a more detailed local characterization of an area's particulate matter.

4.1.1. Needed Network Design Enhancements

The Strategy presents an opportunity to reconfigure ambient air monitoring networks to accommodate identified measurement needs and improved technologies. Experience over the last 20 years suggests four basic enhancements that can be implemented in national network design by:

1) allowing for **multiple and collocated pollutant measurements** to better diagnose cause-effect phenomena between public health effects and air pollution and atmospheric processes;

2) characterizing **regional scale air quality** to understand the linkage between background and transport concentrations (regional, continental, global scales) as they affect rural and urban environments. This need has become increasingly important as the separation in pollutant concentrations between rural and urban air pollution levels continue to decrease;

3) **accommodating new technologies** to provide timely reporting of air quality information to the public and to improve basic characterization of physical, chemical, temporal, and spatial composition of air quality; and

4) **improving flexibility** to: (1) incorporate future monitoring of new pollutants, and (2) meet local air monitoring needs.

Consistent with these enhancements, the NMSC has identified the following areas for enhancement:

- greater characterization of hazardous air pollutants (HAPs);
- additional continuous particulate matter monitoring;
- additional information transfer and delivery to the public; and
- integration across pollutant programs.

This proposal for a National Core (NCore) network is intended as a modest set of actions to accommodate these enhancements, while striving to work within the near-zero-sum framework of the strategy.

4.1.2 Rationale for Multi-pollutant Sampling and Spatial Mapping

There are many advantages in shifting toward a multi-pollutant monitoring network. The three main reasons are cited below.

1. **Minimizing monitoring site operational expenses**. A central site with several instruments requires far less travel time and site attention and maintenance than a diffuse network, assuming, of course, attendant reductions in single pollutant sites.

2. **Fostering integrated air quality management**. For years we have recognized the administrative burden of working in a single pollutant framework, when we understand an array of technical linkages across air pollutant categories. From an emission source perspective, mobile and stationary combustion sources simultaneously emit ozone and PM precursors as well as a host of hazardous air pollutants. Numerous chemical and physical atmospheric processes either link several pollutant categories or operate in parallel. Examples include the shared mix of precursors (i.e., primary emissions), intermediate and sink species that link ozone and fine particulate matter (and haze); the adsorption dynamics where particles act as carriers of various hazardous air pollutants; numerous transformations where oxidant precursors (e.g., xylene, toluene, pinenes) are capable of transforming into organic aerosols, specific HAP compounds such as formaldehyde that act as an ozone precursor and through chemical pathways influence particle formation. The list of examples is endless and provides a motivation for integration. However, the intention is not to imply that every aspect of air pollution is integrated as such linkages often exhibit a variety of seasonal and

location dependencies. Nevertheless, the historical emphasis on single pollutant programs needs to move toward more integrated approaches, and air monitoring is a key air program infrastructure component that should facilitate progress.

3. **Supporting national level air quality models and health assessments**. Two examples are provided:

Example 1. Air Quality Model Simulation evaluation:
Air quality simulation models (AQSMs) combine an array of emissions, atmospheric chemical and physical dynamics to serve as important tools for developing emission control strategies and attainment demonstrations. The structure of AQSMs is based on an integrated multi-pollutant framework. Questions have been raised regarding the role of routine networks in evaluating models. For example, diagnostic (e.g., stressing the model to determine if it reproduces observations for the right reasons) model evaluation requires short period intensive field campaigns incorporating vertical chemical/physical profiling throughout the troposphere and research grade measurements of complex radical and sink species, typically beyond the scope of SLT operated routine networks. Diagnostic model evaluation complements the need for basic operational (i.e., does the model generally reproduce observations of important precursor and product species) AQSM evaluations that may span an entire year or more, and be subject to specific episodes of concern not covered in an intensive field campaign. Nevertheless, there have been misconceptions associated with the relevancy of routine data in the model evaluation process and concerns that routine operations be moved toward more "research" grade measurements to support modeling. Some of this concern is perhaps traced back to the role of ozone models in estimating the high 1-hour prediction. Comfort levels on model performance were focused on a few summer-based high concentration episodes, and model performance during other seasons was not a priority. The change in ozone standards to a lower value 8-hour average, and the dominance of the annual $PM_{2.5}$ standard require our models to perform well (and be evaluated) over more diverse time and meteorological regimes. Moreover, the large regional behavior of ozone and $PM_{2.5}$ present national level issues that result in the AQSMs (e.g., CMAModels 3, REMSAD) applied over large spatial domains covering the entire contiguous United States. As the models are now applied over increasingly larger spatial and time scales, the monitoring networks must adopt and provide a minimum level of support for their evaluation. Finally, an infrastructure of routine measurements, even during those intensive field campaigns designed for diagnostic model evaluation, are required.

Three very critical components of NCore address the model evaluation needs: spatial mapping, multi-pollutant measurements and continuous data. From an operational model evaluation perspective, models attempt to replicate major surface scale features of the primary pollutants of interest, largely $PM_{2.5}$ and ozone. The emphasis on mapping as a national need for public information purposes is just as critical for AQSM evaluation, as well as other emissions strategy elements (e.g., defining planning areas and tracking progress over time) and health and exposure assessments. (See example 2.) The leveraging of collocated pollutants improves the ability to evaluate models by providing greater challenge to testing more than one State variable at a time. In effect, the availability of important collocated species restricts the ability to subjectively improve model performance and can serve to identify areas need for improvement. The core multi-pollutant species were chosen as key species from both model evaluation and health assessment perspectives. Finally, the emphasis on continuous data is valued from a model evaluation perspective. Although one role of a model may be to estimate an annual average, AQSMs generally calculate predictions over small time intervals and typically can provide output at one-hour time intervals. The ability to test model's temporal behavior benefits both short and long-term predictive ability as errors at small time scales can aggregate easily to cause problems over large time scales.

While this discussion has emphasized the use of data in evaluating model performance, a far more important integration across observations and models must be fostered through the air quality community. Calculated model concentrations and observations are all predictions: they just use different tools or formulations to arrive at the same product. A point measurement based on "measurement determined" observation is perhaps no more representative of the larger area of volume of concern than that developed through a "model." In a sense, modeled data and measured data all are predictive results from the spatial and temporal perspective from which we interpret data. We need to make much better progress in integrating modeling and monitoring techniques and take advantage of the maximum benefits derived from their highly synergistic usage. An opportunity is now presented to meld real-time modeling data that are corrected or "nudged" by the observations to produce our best and most timely representations of more complete spatial surfaces. Such surfaces are part of the future vision for linking observations and model predictions through the information transfer initiative being conducted nationally through NCore. Similarly, the use of spatial fields have multiple benefits for air quality planning and tracking which will improve with our ability to characterize spatial fields over frequent time intervals.

Other observational techniques benefits from NCore multi-pollutant sites, and include source apportionment models that connect emission source categories with receptors (measurements) and observational based models (OBMs) that use measurements to infer precursor control preferences (e.g., NOx or VOC for ozone; NH3 or NOx for PM). Again, these tools as well as predictive models all together require basic inputs and checks for their operation.

Collectively, with direct observations all the modeling tools applied in both traditional and unique means are used in “weight-of- evidence” schemes to develop practical emission reductions strategies.

Example 2. Health and exposure assessments for NAAQS reviews
Many of the arguments for model evaluation apply to exposure and health assessments. First, we have a national need to maintain a minimum core network to support long-term exposure and epidemiological assessments that factor into the recurring 5-year reviews of the NAAQS. To be clear, NCore supplies only a basic infrastructure of routine measurements, not personal or indoor monitoring that is necessary for exposure assessments. NCore will, however, provide key centralized monitoring data from which to relate back to more detailed microscale and other ambient exposure related measurements. Similarly, NCore will not collect all of the suspected particulate-matter-related agents hypothesized to be key players in the direct adverse health impacts associated with PM (e.g., soluble metals, ultra fine particles, and biological matter). Health assessments attempt to develop causative relationships between specific air pollution parameters and adverse health effects, which benefits from sampling a variety of pollutants over a range of diverse populations, covering different air quality conditions brought on by different climatologies and emissions patterns (i.e., mix and strengths of source types). Multiple pollutant species need to be sampled at different locations to better delineate the effects of a particular species by teasing out a range of confounding factors associated with interactive effects among different pollutants. Accordingly, NCore should measure multiple pollutants across a diverse group of platforms reflecting a range of populations, climatology and air quality composition across the United States.

4.2 Attributes of NCore

The NCore network is envisioned to be a long-standing stable network that should be viewed as a “minimum” infrastructure to address major national monitoring objectives. These national objectives and other attributes are used as a starting point for design. In describing national objectives, a substantial degree of overlap with area-specific objectives in aspects of network design will emerge. That is part of the overall optimization and leveraging that is intended. The scope of this activity retains the focus on traditional networks operated by SLTs. National needs beyond these that include ecosystem welfare assessments, global atmospheric transport and diagnostic research need to be integrated as part of the leveraging optimization process (addressed later in this section).

In developing the overall objectives for the Strategy, the NMSC also developed objectives for the NCore component, and these objectives are referred to as “attributes,” so as not to be confused with the Strategy objectives. The NCore attributes are as follows:

- To satisfy the minimal level of national ambient air monitoring needs, including:
    - real-time input of data from across the country (e.g., AIRNow) using continuous technologies for timely dissemination to the public and supporting:
        - spatial mapping
        - public health advisories
        - public air quality forecasts
    - emissions strategy development, including:
        - routine/operational model evaluation
        - observational and source apportionment techniques
        - defining nonattainment and emissions strategy regions
    - tracking air quality trends and progress, such as
        - accountability of major national emissions strategies
        - health/welfare assessments (e.g., for HAPS, visibility)
    - NAAQS determinations (i.e., compliance with standards)
    - health assessments that influence periodic NAAQS reviews (i.e., 5-yr EPA review process)

- To provide a consistent national network of multi-pollutant measuring sites;

- To provide consistent air quality information for both urban and rural areas;

- To provide a basis from which the augmentation by state/local/tribal monitoring networks can be utilized to meet SLT monitoring priorities;

- To accommodate the national needs for monitoring new pollutants (e.g., air toxics, $PM_{(10-2.5)}$);

- To maximize leveraging of existing air monitoring sites, especially those with multi-pollutant capabilities; and

- To the degree it can be accommodated, provide data and other support for essential science needs, such as:

    - health/exposure studies
    - evaluation of new monitoring methods
    - characterization of atmospheric processes and source-receptor relationships (e.g., air quality model evaluation; source characterization techniques).

4.3 The National Component

NCore is intended to address national level data needs that often are a secondary concern of historical networks that were designed from a single pollutant and often local area perspective. NCore does not address explicitly those monitoring needs associated with a local/flexible component. Rather, by defining a modest national network, the capacity (or flexibility) to support local needs is protected. Additional discussion on this balance between national and local needs is provided below and in the document summary. Throughout this document there is far more discussion addressing "national" needs, a natural outcome as all parties have a vested interest in a larger national picture. However, this emphasis on national needs should not be construed as elevating national over local needs. Details of the attributes for the national component are given below.

4.3.1 Public Information

The acquisition of real-time data from across the country (e.g., through AIRNow) using continuous technologies for timely dissemination to the public is a central element to NCore. Such information could drive national mapping programs for $PM_{2.5}$ and ozone reported from AIRNow, and further support public air quality forecasts and public health advisories for various pollutants. To date, AIRNow has effectively used and evolved into a national resource built upon available data sources from an array of State and local networks designed for non-mapping purposes. By specifying mapping as a national objective, network spatial design tools can be applied to optimize the existing networks with a cohesive central mapping theme that lends itself to other applications, including emission strategy development and compliance.

4.3.2 Emissions Strategy Development

The development of emission reduction strategies relies on large regional to national scale air quality simulation models as one of several tools in combination with various area-specific analyses. Models require evaluations which occur at different spatial scales and levels of complexity. National level models often undergo fairly routine "operational" level evaluations that rely on routinely collected data. These routine operational evaluations complement more complex diagnostic evaluations utilizing aircraft data, and research grade measurements of atmospheric intermediate and end products. In application, three types of monitoring approaches are used for model evaluation. First, the NCore component would support much of the operational evaluations of Air Quality Simulation Models (AQSMs), principally by ensuring broad and consistent geographic coverage. Second, the availability of routine data from local oriented networks and mapping related networks (e.g., AIRNow) would enhance the spatial richness of observations for evaluation purposes. And third, routine measurements from NCore would complement intensive field campaigns that provide more complex detailed measurements (e.g., time, space and composition) for diagnostic evaluations.

Numerous source apportionment and other observation-driven models attempt to use measurements directly to associate source-receptor effects and infer emissions reduction approaches even in nonlinear systems. While the application of these tools tend to be area specific, the availability of NCore sites that include multiple collocated measurements will provide significant benefits and also allow for consistent national level applications.

Mapping tools delivering public information should strive to minimize concentration surface error and produce coherent pollutant concentration patterns which can guide emissions strategy development.

4.3.3. Tracking Air Quality Trends and Emissions Strategy Progress

NCore would provide the primary input to track national air quality trends of a range of noncriteria and precursor pollutants as reported in EPA's annual air quality trends and related reports. NCore also would accommodate an important accountability component of air quality trends, which tend to place somewhat greater emphasis on directly emitted precursor species to determine if emission strategies are being implemented as originally intended. For accountability purposes, consideration must be given to locating some NCore sites in rural representative locations with instrumentation capable of detecting long term emission changes associated with implementation of national programs such as Title IV, the NOx SIP calls, and the Clear Skies program (nitrogen, sulfur, mercury). Program tracking also would include national visibility assessments as well as a selected limited group of hazardous air pollutants (HAPs) that tend to be of concern in numerous locations nationwide.

4.3.4. Support Health Assessments and Periodic NAAQS Reviews

Historically, much of the underlying health effects research has relied on routinely available data to associate various adverse health impacts with air quality. NCore would provide a diversity of monitoring locations across the nation to provide a stable base of data for long-term health assessments. (See, for example, Attachment 4-1, "Air Quality Monitoring in Support of Epidemiology.") These health assessments require basic "representative" air quality data of several common pollutants across a diversity of population and emission regimes. The NCore design will emphasize the importance of capturing diverse locations and provide a minimum group of routinely collocated measurements that will assist both health assessment and emissions strategy development needs. More advanced air quality measurements would be conducted through collaborative research endeavors and not directly supported by state/local agencies and Tribes. However, where possible the development of NCore platforms should anticipate the need for possible collaborative work ranging from toxicologists choosing to collect occasional "mega" aerosol samples, to atmospheric scientists conducting research grade measurement studies. Therefore, platform capacity, space and power specifications, generally should be designed to avoid future extensive retrofitting.

4.3.5 Compliance

NCore will be used for basic comparisons to the NAAQS. Traditionally, monitoring for NAAQS comparisons has been more of a localized objective brought about by national regulations. Increasingly, the extent of non-attainment for our principal criteria pollutants (i.e., $PM_{2.5}$ and ozone) has become, in many instances, more of a regionalized issue due to numerous factors including shifting demographics away from urban centers, widespread homogeneous behaviors of $PM_{2.5}$ aerosols in many eastern U.S. locations, and the shift to a lower concentration 8-hour ozone NAAQS. Here again, the characterization of concentration surfaces through mapping requires both national and local perspectives.

4.3.6 Support Science Studies

Many of the previous objectives discussed the complementary role routine networks play in supporting research. Routine data generally complement more intensive research-oriented efforts spanning a range of atmospheric process and health assessment studies. While NCore design will be driven to address non-research objectives, the overlap between research and regulatory needs is substantive and it is imperative that NCore be viewed as an important research resource. To that end, components of the NCore network should facilitate collaborative work with research institutions in a manner similar to the Supersite program for $PM_{2.5}$. Certain NCore platforms could serve an important instrument evaluation need at a national level. NCore will therefore include a limited number (probably in the order of 3 to 8) of collocated multi-pollutant sites that serve primarily the scientific objectives listed above. Collocation also provides opportunities for diagnosing measurement methodology issues as the more complete characterization of atmospheric chemistry provides enormous insight into likely causes of measurement artifacts. The concept is not that routine grant programs for state/local/ agencies and Tribes siphon their resources to support research institutions, but rather that a greater level of complementary work across research and regulatory agencies is engendered as part of the NCore design which provides more optimized benefits for all parties. As platform capacity is reviewed for accommodating new measurements, enhanced capacity should be built in for collaborative work where researchers may need to use platforms for short periods of time to collect large samples of aerosols for toxicological studies, or operate research grade measurements in concert with more routine instrumentation.

Other broad based national air monitoring objectives include ecosystem welfare assessments, characterization of global/continental level transport phenomena, and explicit research objectives. The objectives listed above are compatible with the existing federal grant structure, where Section 103 and 105 Grants are administered by EPA to state and local agencies, and Tribes. Nevertheless, significant integration and optimization opportunities exist to link with these other major national objectives.

4.4 The Local Component

The development of NCore does not replace the role of localized networks, and no premise is made on the relative importance of national versus local needs. In looking at the local component, the NMSC established several objectives, or attributes, to clearly delineate the intent to address local concerns. The following listing of attributes illustrates some of the major differences between the national NCore component and the more flexible component of state/local/tribal networks:

- To address state/local/tribal concerns not adequately addressed through NCore. Examples include:
    - "hot spot" or mobile monitoring for air toxics
    - source-specific monitoring
    - community/environmental justice concerns
    - emissions reduction strategy assessments
    - tracking non-criteria pollutants of concern
    - NAAQS designation requests
    - enhanced monitoring as needed for local characterizations of key pollutants and/or their precursors

- To establish the highest priorities for state/local/tribal air monitoring needs and utilize local flexibility to shift resources to meet those needs, including the reduction of inefficient monitors and the addition of value-added monitors as necessary.

- To utilize data such that the benefits of the NCore network can be enhanced.

- To meet federally-recommended monitoring objectives to the degree possible.

4.5 NCore Structure

NCore would be structured as a three-tiered approach (see Figure 4-1), based on measurement complexity, ranging from the most (Level 1) to the least (Level 3) complex. A range of 3 to 10 Level 1 "master" sites, based on available resources, would serve a strong science and technology transfer role for the network. Approximately 75 Level 2 sites would add a new multiple pollutant component to the networks, with emphasis on continuously operating instruments. In many areas, location of a Level 2 site, as appropriate, in conjunction with existing PM speciation, PAMS and/or air toxics trends sites, would optimize leveraging of existing resources to meet Level 2 objectives. Level 3 sites are largely single pollutant sites, emphasizing the need for a spatially rich network in the most ubiquitous criteria pollutants (i.e., $PM_{2.5}$ and ozone) and addressing an assortment of compliance related needs. Progressing from Levels 1 through 3, the character of these sites moves from a strong science orientation toward compliance. A summary of measurement parameters for these levels is provided in Table 4-1.

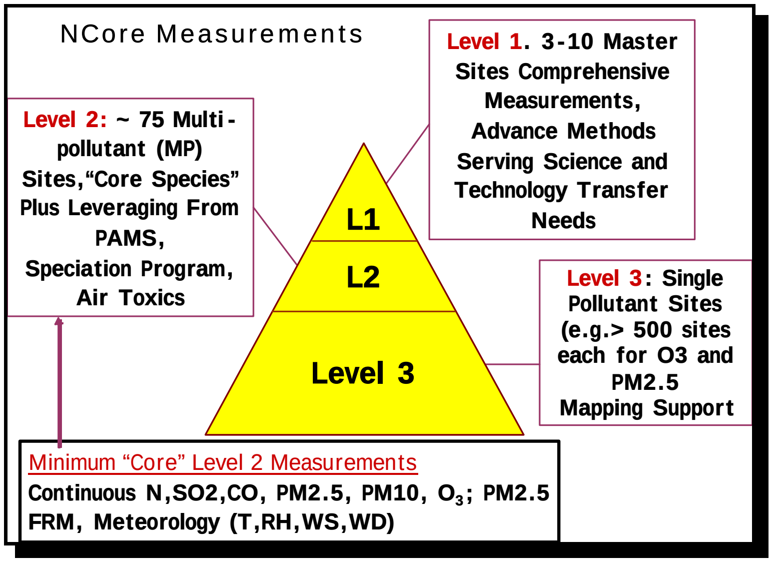


FIGURE 4.1 Components of NCore.

4.5.1. Level 1

There would be a small number (e.g., 3 to 10) of Level 1 "master" sites, or "supersites," which would include the most comprehensive list of routine measurements required for the Level 2 sites (see next subsection), plus research level measurements with potential for routine application (e.g., PM size distribution, nitric acid, ammonia, true NO_2).[1] Level 1 sites could include additional measurements dependent on area-specific priorities, available expertise, and resources. These sites would serve three needs: (1) a comprehensive suite of measurements providing the most insightful of all routine air monitoring networks; (2) a technology transfer mechanism to test emerging methods at a few locations with disparate conditions that eventually would find more mainstream application[2] and (3) a bridge across routine applications and science.

Over the last 10 years, EPA's Office of Research and Development has gradually decreased its level of methods development and testing to a point where it no longer is considered a leader in this field. Methods testing now is conducted through a rather loose collection of state-sponsored trials (especially California's Air Resources Board), vendor sponsored initiatives, miscellaneous research grants, and agreements to

[1]NO and NOy are chosen as they provide indicators for relatively fresh (NO) and aged (NOy) emissions. They provide a critical tool in accounting for progress in large-scale nitrogen emission reduction programs (e.g., NOx SIP calls and Clear Skies, provide input for a variety of observational based and source apportionment models, and assist evaluation of air quality models. True nitrogen dioxide, NO_2, should be added as a core measurement. However, the lack of affordable and routinely operational instrumentation prevents such a recommendation at this time.

[2]True nitrogen dioxide measurements should be part of routine operations; however, field testing and demonstration efforts must precede application in routine networks. Consideration for future routine applications should also be given to other measurements such as continuous ammonia, nitric acid, and particle size distributions.

universities (e.g., PM Supersites and health centers), combined with a skeleton level of effort of internal EPA testing. The PM Supersites program does fulfill some of the needed technology transfer needs, but is of short duration and mostly focused on a broad array of particle characterization issues in addition to technology testing. Level 1 sites would be one component addressing this national level weakness that needs attention. State agencies cannot continue to be burdened with being "trial" testers of new methods. More importantly, there is a pressing need to avoid losing the opportunities in greatly enhanced data value that emerging technologies present.

4.5.2. Level 2

Level 2 measurements represent the mainstream multiple pollutant, or "backbone," sites in the network. The approximate total number of 75 national sites, as well as the proposed measurements, is a modest recommendation. This approach introduces a reasonable and manageable realignment in the networks. Site locations will be based on design criteria that balance technical needs with practical considerations such as leveraging established sites and maintaining geographic equity. There are key design features which embody the purpose of the Level 2 sites:

1. **Use of continuously operating instruments:**
   Continuous systems allow for immediate data delivery through state-of-the-art telemetry transfer and support reporting mechanisms such as AIRNow and a variety of public health and monitoring agencies charged with informing the public on air quality. Continuous data add considerable insight to health assessments that address a variety of averaging times, source apportionment studies that relate impacts to direct emission sources, and air quality models that need to perform adequately over a variety of time scales to increase confidence in projected emissions control scenarios.

2. **Diversity of "representative" locations:**
   Diversity across urban (e.g., large and medium size cities) and rural locations is essential to properly characterize typical urban environments as well as background and transport corridors. National level health assessments and air quality model evaluations require data representative of broad urban (e.g., 5 to 40 km) and regional/rural (> 50 km) spatial scales. Long-term epidemiological studies that support the review of national ambient air quality standards benefit from a variety of airshed characteristics across different population regimes. The NCore Level 2 sites should be perceived as developing a representative report card on air quality across the nation, capable of delineating differences among geographic and climatological regions. While "high" concentration levels will characterize many urban areas in NCore, it is important to include cities that also experience less elevated pollution levels, or differing mixtures of pollutants for more statistically robust assessments. It also is important to characterize rural/regional environments to understand background conditions, transport corridors, regional-urban dynamics, and influences of global transport. Air quality modeling domains continue to increase. Throughout the 1970's and

1980's, localized source-oriented dispersion modeling evolved into broader urban scale modeling (e.g., EKMA and urban airshed modeling for ozone), to regional approaches in the 1980's and 1990's (e.g., Regional Oxidant [ROM] and Acid Deposition [RADM] Models), to current national scale approaches (Models 3-CMAQ), and eventually to routine applications of continental/global scale models. The movement toward broader spatial scale models coincides with increased importance of the regional/rural/transport environment on urban conditions. As peak urban air pollution levels decline, slowly increasing background levels impart greater relative influence on air quality. Models need to capture these rural attributes to be successful to provide accurate urban concentrations.

3. **Collocated multiple pollutant measurements:**
   Air pollution phenomena involving ozone, particulate matter, other criteria pollutants, and air toxics are more integrated than the existing single pollutant program infrastructure suggests. From an emissions source perspective, multiple pollutants or their precursors are released simultaneously (e.g., combustion plume with nitrogen, carbon, hydrocarbon, mercury and sulfur gases and particulate matter). Meteorological processes that shape pollutant movement, atmospheric transformations, and removal act on all pollutants. Numerous chemical/physical interactions exist underlying the dynamics of particle and ozone formation and the adherence of air toxics on surfaces of particles. The overwhelming programmatic and scientific interactions across pollutants demand a movement toward integrated air quality management. Collocated air monitoring will benefit health assessments, emission strategy development and monitoring. Health studies with access to multiple pollutant data will be better positioned to tease out confounding effects of different pollutants, particularly when a variety concentration, composition, and population types are included. The tools for strategy development (e.g., air quality models and source attribution methods) are enhanced by utilizing more robust evaluations (i.e., checking performance on several variables to ensure model produces results for correct reasons and not through compensating errors). Just as emission sources are characterized by a multiplicity of pollutant release, related source apportionment models yield more conclusive results from use of multiple measurements. Monitoring operations benefit by a streamlining of operations and by multiple measurements which can potentially diagnose factors affecting instrument behavior. In addition, the movement toward integrating continuous PM (mass and speciation) monitors, at this juncture, requires care in preserving at least some number of collocated filter and continuous instruments.

The minimum recommended measurements, through near-continuous monitors reporting at 1-hour intervals or less, include gaseous sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen oxide and total reactive nitrogen (NO and NOx or NOy), ozone (O_3); $PM_{2.5}$; and PM_{10}. Additional parameters include filter-based $PM_{2.5}$, as measured with FRMs, and basic meteorological parameters (temperature, relative humidity, wind speed and direction). While these parameters include most criteria pollutants, except for nitrogen dioxide and lead, they are not chosen for compliance purposes. They represent a robust set of indicators that support multiple objectives of NCore. In most cases, these minimum measurements will be accompanied with measurements from other existing programs, such as PAMS or PM speciation to maximize the leveraging of greater multi-pollutant availability.

The continuous PM measurements are not expected to use FRM monitors, as currently, no $PM_{2.5}$ continuous monitor has equivalency status. The reason for specifying continuous methods for PM has been addressed at length. The intention here is not to produce independent PM_{10} values, but to provide a mechanism to develop an organized and consistent $PM_{(10-2.5)}$ data base that will be supportive of health studies and emission strategy development. As a peripheral benefit, the development of this data base should meet equivalency testing requirements for a $PM_{(10-2.5)}$ method and perhaps be viewed as the default "regulatory" method for $PM_{(10-2.5)}$. Collocation with FRMs is an important component of the $PM_{2.5}$ continuous implementation strategy, as the relationship between FRMs and continuous monitors drives the integration of these systems. These relationships will vary in place and time as a function of aerosol composition (e.g., gradual evolution of a more volatile aerosol in the East as carbon and nitrate fractions increase relative to more stable sulfate fraction).

4.5.2.1. Future NCore Level 2 Measurements

The minimum recommended NCore Level 2 measurements reflect a balance across a constrained resource pool, available monitoring technologies, and desired measurements. Consideration should be given to introducing additional Level 2 measurements at selected sites in the future. Examples of nationally important measurements that support multiple objectives include true nitrogen dioxide, nitric acid and ammonia gases. Consideration also should be given to routine size distribution measurements at selected locations. As multiple pollutant stations, NCore sites should over-design for space and power consumption with the expectation of additional future measurements. Such over-design will encourage collaboration between research scientists and government agencies as NCore Level 2 sites should accommodate periodic visits from health and atmospheric scientists that may conduct specialized intensive sampling.

4.5.3. Level 3

Level 3 sites are intended to meet the needs for greater monitoring density for the key pollutants of concern, which currently is ozone, $PM_{2.5}$, and in some areas, mainly in the west, PM_{10}. Also, some highly localized carbon monoxide nonattainment areas may still exist. For these key pollutants, and for those nonattainment areas, it is still necessary to maintain a sufficient number of monitors to address the issues associated with SIP development and compliance, as well as other related issues. The Level 3 monitors, therefore, primarily fit this purpose. Such monitors can be single or multi-pollutant, as needed, to address the issues of concern. Examples of conditions, which the Level 3 monitors can address, include:

- documenting the site with the highest concentration
- determining appropriate nonattainment boundaries
- determining local background conditions
- estimating population exposure
- characterizing local conditions
- determining trends
- complementing Level-2 sites in assessing effectiveness of local emissions reduction programs

It is expected that the Level 3 sites will be comprised primarily of existing NAMS/SLAMS sites, since many of the NAMS/SLAMS sites are already satisfying the above set of conditions. The number of Level 3 sites will be based on a combination of local needs and the network assessment process, but clearly, the number of such sites nationally will be far greater than the number of Level 1 and 2 sites.

It is further expected that, at a minimum, new information transfer technologies can be incorporated into the Level 3 sites so that the rapid transfer of data to the public is accomplished consistent with the objectives of the Strategy. To that end, even though the total number of monitors will be less than now exists, the number of monitors reporting, for example, to AIRNow or local websites, should increase over what is readily available today.

<table>
<tr><td colspan="5">Table 4- 1: Detailed list of NCore measurements</td></tr>
<tr><td colspan="3">Site level
{Approximate site total*}</td><td>Parameter</td><td>comments</td></tr>
<tr><td rowspan="14">L
E
V
E
L

1

3
to

10</td><td rowspan="7">Level 2
“core”

{70-100}</td><td rowspan="2">Level 3
(one of)
{500 -800}</td><td>ozone</td><td></td></tr>
<tr><td>PM2.5</td><td>Continuous and filter at level 2 sites; emphasis on continuous at Level 3 sites for AIRNow</td></tr>
<tr><td rowspan="5"></td><td>Basic
<u>Meteorology</u></td><td>temp, RH, ws,wd, [surface level]</td></tr>
<tr><td><u>PM10</u></td><td>continuous; only filter based at critical Level 2 sites with potential NAAQS (future) violations</td></tr>
<tr><td><u>CO</u></td><td>requires funding</td></tr>
<tr><td><u>SO2</u></td><td>requires funding</td></tr>
<tr><td><u>NO/NOy</u></td><td>requires funding</td></tr>
<tr><td>Level 2
core
plus
standard
speciation
{40-70}</td><td></td><td>Filter based PM2.5 speciation as in trends</td><td>every third day, 24 hr sample; major ions through IC; elements through XRF, EC and OC fractions through combustion</td></tr>
<tr><td>core plus
standard
and
continuous
speciation
{10}</td><td></td><td>daily/continuous PM2.5 speciation</td><td>includes the 10-15 continuous nitrate, sulfate and carbon measurement sites that were added to speciation trends as part of earlier agreements with NAS/CASAC</td></tr>
<tr><td rowspan="5">core plus
“national
HAPs and
standard
speciation
{10-25}</td><td rowspan="5"># sites dependent on number of HAPs trends and degree of collocation across speciation</td><td>formaldehyde</td><td rowspan="5">currently proposed national HAPs trends measurements to be collocated with PM2.5 speciation (some unknown subset of daily speciation sites included)</td></tr>
<tr><td>benzene</td></tr>
<tr><td>acrolein</td></tr>
<tr><td>chromium</td></tr>
<tr><td>light absorbing aerosol</td></tr>
</table>

	core plus speciation and PAMS {15-25}		VOC	**minimum PAMS** also includes Level 2 core species CO and NO/NOx/NOy; recommend both continuous TNMOC (year round to support HAPs surrogate) analyzer and mix of annual/seasonal canister or auto GC sampling for specific compounds...one type 2 site per current PAMS city
	core plus speciation plus PAMS plus HAPS {8-20}	Number of sites dependent on ability to collocate	all of above	
	Level 1 specific	Level 1 sites include all above measurements plus next column	real NO2	not routine measurements at this time
			nitric acid	
			ammonia	
			PM size distribution	
			PM ultra fine	
			SVOC	
	* site numbers are not additive; e.g., all level 1 are part of level 2; all level 2 are part of level 3 ___instrumentation resources required...see section 4.12			

4.6 NCore Siting

4.6.1 Level 2

The siting goal for Level 2 NCore sites is to produce a sample of representative measurement stations to service multiple objectives. Siting objectives include:

A. Collectively:

- approximately 75 locations predominantly urban with 10-20 rural/regional sites;

- for urban areas, across-section of urban cities, emphasizing major areas with > 1,000,000 population, and including a mix of large (500,000 – 1 million) and medium (250,000 – 500,000) with geographically and air quality diverse locations suitable as reference sites for long-term purposes;

- for rural areas, capturing important transport corridors, both internal, across-border (e.g., Canada and Mexico), and intercontinental, as well as background regionally representative conditions. In addition, some sites should allow for characterizing urban-regional coupling (e.g., how much additional aerosol does the urban environment add to a larger regional mix).

- On an individual site basis:

  - establishing "representative" locations on a scale of 5 to 15 km for urban sites, and greater than 50 km for rural sites, and not impacted by local sources. The important criteria are to minimize local impacts in urban areas and, in rural areas, achieve broad spatial representation associated with secondary formation of aerosols and ozone that can be delineated from urban excess contributions.

  - leveraging with existing sites where practical, such as the speciation, air toxics and PAMS, and Clean Air Status (CASTNET) trends sites.

  - assuring consistency with collective criteria

  - consideration of other factors, such as resource allocation and level of Tribal participation.

4.6.1.1 Broad-based Technical Guidance

Level 2 network design is initiated by first considering a cross-section of urban locations to support long-term objectives, such as epidemiological studies, then adding rural locations to support the broad national objectives, including air quality modeling evaluation, emissions strategy accountability assessments, and trends/inter-regional comparisons. This is followed by a practical mapping of general locations with existing sites, and an equitable and objective allocation scheme. This sequential approach is captured in **Figure 4-2.** The top two segments of this figure represent, in general terms, the “needed sites,” whereas the bottom two segments are examples of “existing sites.” The intent is to maximize the existing site inventory in establishing Level 2 sites. (A complete set of existing network site location maps is contained in **Attachment 4.2**.)

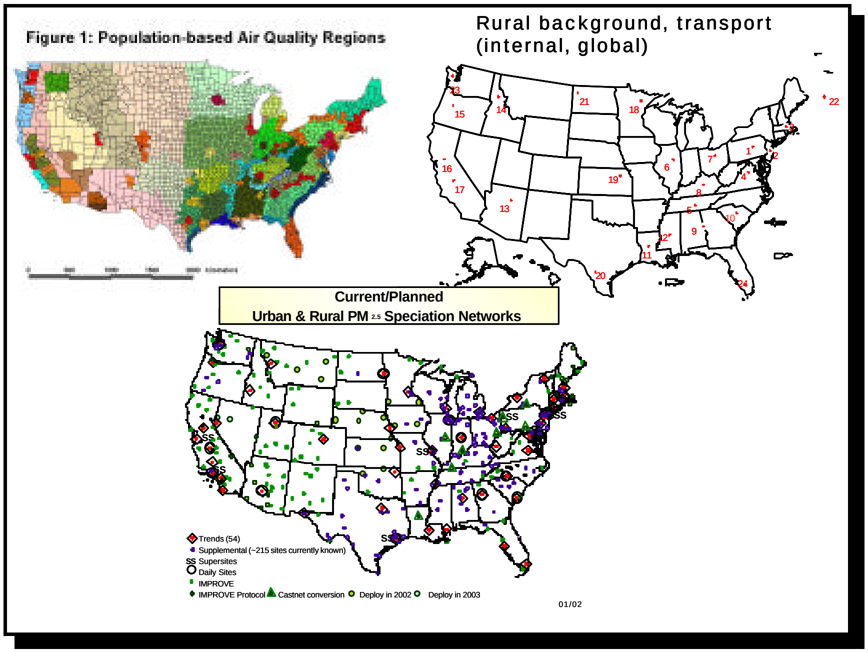


Figure 4-2. National maps providing initial broad scale siting guidance for NCore level 2 sites. The maps include recommendations based on supporting long term health assessments (top left) that emphasize an aggregate of representative cities and air quality mode evaluations that rely on rural background and transport locations (top right). Existing site locations in most cases will be used as NCore siting infrastructure (bottom).

Nearly 80 “representative” air quality regions that group populations based on statistical and geographic factors form a cross-section of desired areas for long-term epidemiological studies. An additional 24 rural locations are identified to support evaluation of the national Community Modeling Air Quality System (CMAQ). These locations can be compared with available site candidates from existing networks (e.g., PM speciation, PAMS type 2 and CASTNET) that were designed with “representative” siting conditions commensurate with NCore Level 2 criteria. This procedure provides a modest objective-based reference to judge the adequacy of site allocation process.

4.6.1.2 Site Allocation Process

In determining how the Level 2 sites should be located, the NMSC felt that an initial proposal ought to consider nationwide equity and the fact that supporting grant funds to the States are not likely to change proportionally to support monitoring needs. Therefore, the initial allocation scheme, as summarized in **Table 4-2**, provides for a minimum of one Level 2 site per State. In addition, consideration for population is the basis for additional monitors, primarily, but not absolutely, in urban areas. Those States without population centers of at least 250,000 would be allocated rural-based Level 2 sites. Technical guidance sets a framework for assessing the development of NCore, while the allocation scheme provides a process for facilitating implementation. This allocation scheme is an initial proposal and generally provides a sweeping range of metropolitan areas. Clearly, allocation must be flexible enough to ensure that sites add meaningful value and avoid redundancies. Suspected shortcomings in the proposed allocation scheme that need to be reconciled include, for example, a lack of rural locations in California, lightly populated western States that may not provide a meaningful rural location, multiple Florida locations with generally moderate air quality due to marine influences, and possible redundant locations along the East Coast and Midwest.

Table 4-2. Proposed NCore Level 2 site allocations.

	Total	Major Cities > 1M	Large Cities 500K - 1M	Medium Cities 250-500K	Rural
1 per State minimum	50				
3 each in most populated States (NY, CA, TX, FL)	8				
2 each in second tier populated States (OH, IL, PA, MI, NC)	5				
additional rural sites	10				
Total	***74***	***32***	***13***	***11***	***18***

NOTE: Allocation does not cover every major, large, medium sized city in the United States; States lack cities > 250,000 provide rural coverage.

4.6.2 Level 1 and Level 3

NCore Level 1 sites are an important bridge for technology transfer and corroboration between research and regulatory oriented organizations. Because the resource prospects for supporting these sites appear limited at this point in time, as it is not part of mainstream routine network, the determination of Level 1 sites will be undertaken when the funding prospects improve. As a guideline, however, these sites should include a range of representative locations across the Nation (e.g., allocating up to one site per EPA Region). Candidate locations could include existing supersites and other well-developed platforms capable of accommodating the space, power, and security needed for a large assortment of instruments. Consideration should be given to developing a rural-based Level 1 site to ensure that technologies tested today can meet future conditions as concentration levels continue to decline.

Level 3 sites retain several NAMS/SLAMS attributes. A large preponderance of Level 3 sites will be designated from the existing NAMS/SLAMS network. Some adjustments to existing networks are appropriate based on the network assessments, but those adjustments may involve re-locating existing monitors to better meet the Level 3 objectives.

4.7. Site Selection and Approval Process

Except for Level 1 sites, it is envisioned that the selection of NCore sites will be undertaken by the host State/local agency or Tribe, but that review and approval will be done by EPA to assure that the recommended locations are consistent with the appropriate NCore site objectives. Since the Level 1 sites are considered the more research-oriented sites, and are dependent on additional funding, it is expected that EPA would take the lead in recommending appropriate Level 1 site locations. These can either be at existing Level 2 sites with adequate logistics to support a Level 1 effort, or an entirely new location. In either case, it would be expected that EPA would coordinate with the host State and/or local agency prior to finalizing the site.

Level 2 sites will be determined by the host agency or Tribe, and will require approval by the EPA Administrator. This approach insures that the collective national siting criteria are adhered to. It is expected that an NCore subcommittee of the larger NMSC will remain in place to assist EPA in assuring the appropriateness of the site locations.

Level 3 sites will be determined by the host agency or Tribe, and will require approval at the EPA Regional Administrator level. The regions are in the best position to understand the full complement of monitoring needs for the Level 3 site objectives, and therefore approval at the regional level is most appropriate.

The local-flexible portion of NCore, which is intended to meet local monitoring objectives, will not require EPA approval. However, SLTs, would be expected to notify EPA that such sites are being established.

4.8 Relationship Between NCore and Existing Networks

Excluding CASTNET and IMPROVE, the existing State and local networks[3] largely consist of NAMS/SLAMS and special purpose/supplemental monitoring for criteria pollutants; PAMS; non-FRM portions of $PM_{2.5}$ network (e.g., speciation, supersites, and continuous mass); and air toxics. Most of these networks include a combination of prescriptive and less prescriptive monitoring based on relatively direct language in 40 CFR part 58 of the monitoring regulations, or through specific guidance in the Federal 103/105 Grants Program. The more prescriptive aspects include NAMS for all criteria pollutants, $PM_{2.5}$ SLAMS, PAMS, speciation trends**,** and the emerging air toxics national trends sites. Less prescriptive elements, not included in the monitoring regulations (i.e., "local-flexible" component), include special purpose/supplemental monitoring, SLAMS (other than PM mass), $PM_{2.5}$ speciation beyond trends, and a variety of air toxics sampling. Note that the estimated local fraction of resources for a particular program element is greatest for air toxics followed by $PM_{2.5}$ speciation. (See **Table 4-3**.) While much of the SLAMS monitoring for criteria pollutants is not required in 40 CFR part 58, over time, the monitoring has taken on a "required" context associated with various Clean Air Act requirements (e.g., design value sites, maintenance plan provisions, new source review, and miscellaneous arbitration).

Table 4.3. Relationship between existing networks and NCore						
	NCore ***Level 1***	***NCore***[1] ***Level 2***	***NCore***[1] ***Level 3***	***Local***	***Other***	***Notes*** ***(All NCore sites support AIRNow)***
PM Supersites	T					*lacking future funds*
NAMS[1] ***(CO, NO2, O3, SO2, PM10, PM2.5)***		T				*specified Level 2 PM2.5, PM10, NO/NOy do not use equivalent methods (assume each site has PM2.5 FRM; cont. PM10 and PM2.5 evolve into equivalent PM* $_{(10\text{-}2.5)}$
SLAMS[1]			T			
PM speciation trends		T			T	*assumes most (not all) trend sites are Level 2 locations*
PM (SIP) speciation				T		
Air toxic trends		T				
Air toxics				T		
PAMS type 2		T		T		*unknown number of PAMS sites for Level 2*
other PAMS				T		
1 - Criteria pollutant trends are generated now from a subset of NAMS and SLAMS, and in the future from NCore Levels 2 and 3.						

A rough comparison of NCore with existing networks suggests the following relationship:

- Level 1 = PM supersites
- Level 2 = criteria pollutant NAMS, speciation trends, air toxics trends, PAMS type-2
- Level 3 = SLAMS criteria pollutants

Several qualifying remarks are appropriate. The Supersites program is temporary and funding to transition into Level 1 master sites is not yet identified. Level 1 sites should be an integral long-term network component, and operate with greater intersite consistency than the current Supersites. The minimum requirements determining criteria pollutant trends (analogous to NAMS), in most cases, would be accomplished through Level 2 sites. It is expected that the majority of speciation trend sites will be selected as Level 2 sites. The emerging national air toxics trend sites (NATTS) are being collocated at existing speciation sites, mostly trend sites, which in turn should emerge as formal NCore Level 2 sites. Approximately 50% of the remaining PAMS type-2 sites also serve as likely candidates for NCore level 2, and many of these already are collocated with speciation trend sites. Note that major fractions of air toxics, PAMS and PM speciation measurements are not part of NCore and should be viewed as part of the "local" network. However, agencies or Tribes supporting PAMS and PM speciation monitoring efforts would be strongly encouraged to integrate these into the Level 2 site structure, thereby providing greater multi-pollutant capabilities than the base Level 2 site.

4.8.1. Relationship to Existing PAMS, $PM_{2.5}$, Air Toxics, and NAMS/SLAMS Networks

The initial deployment phase of NCore relies on substantial leveraging from existing and emerging (e.g., air toxics) air monitoring networks. NCore would assume the "national" level or trend components of these programs. A more detailed discussion of these relationships is given below:

- **Air Toxics** Current discussions with the Air Toxics Steering Committee indicate a relatively small trends network with 10 to 20 sites established over the next 2 to 3 years covering a small group of hazardous air pollutants (HAPs) with "national" level importance (i.e., concentration predictions appearing in many places at levels of concern). More than 50% of the base air toxics monitoring resources would be dedicated to local needs. These trend sites could appropriately be located at Level 2 NCore sites.

- **$PM_{2.5}$ Speciation** The speciation trends sites are excellent candidates to initiate siting locations for Level 2 multi-pollutant sites. The model established for the speciation program with approximately 50 national trends sites and nearly 200 SLT supplemental sites reflect the value associated with both local and national needs, and a blueprint for much of the development of NCore.

- **$PM_{2.5}$ Mass** Recent spatial analyses of these sites are forming an important tool for larger implementation issues associated with abating $PM_{2.5}$ levels throughout the United States. These sites will be assimilated into additional mapping tools such as AIRNow to provide forecasting and timely public access to AQI related information. The transition to continuous samplers, which requires a reduction in FRM samplers, is critically important. A substantial subset of $PM_{2.5}$ sites will be assimilated into the Level 3 sites.

- **<u>PAMS</u>** A side workgroup of the regulatory workgroup has developed a set of "minimum" PAMS recommendations. (See **Table 4-4**). The Type 2 PAMS sites included in this list of minimum requirements would be considered part of NCore. This revision was initiated in the January, 2000 PAMS workshop in Las Vegas and was based on redefining PAMS objectives. The PAMS principal objective now focuses on the longer term trends and accountability aspects, while playing a supporting role on other emissions strategy development objectives such as model evaluation.

Table 4-4. MINIMUM REQUIRED PAMS MONITORING LOCATIONS AND FREQUENCIES

Measurement	Where Required	Sampling Frequency (All daily except for upper air meteorology)[1]
Speciated VOC[2]	Two sites per area, one of which must be a Type 2 Site.	During the PAMS season: 1) Hourly auto GC, or 2) Eight 3-hour canisters, or 3) 1 morning and 1 afternoon canister with a 3-hour or less averaging time plus Continuous Total Non-methane Hydrocarbon measurement.
NOx	All Type 2 Sites	Hourly during the ozone season[3]
NOy	One site per area at the Type 3 or Type 1 Site	Hourly during the ozone season
CO (ppb level)	One per Type 2 Site	Hourly during the ozone season
Ozone	All sites	Hourly during the ozone season
Surface Met	All sites	Hourly during the ozone season
Upper Air Meteorology	One representative location within PAMS area	Sampling frequency must be approved as part of the PAMS Network Description described in 40 CFR 58.41.

[1]Daily or with an approved alternative plan.
[2]Speciated VOC is defined in the Technical Guidance Document Reference _, Target Compounds.
[3]Approved ozone season as stipulated in 40CFR58, Reference --

- **<u>NAMS/SLAMs</u>** Components of the ozone sites in the current NAMS/SLAMS formulation will primarily be incorporated into the Level 3 adjunct sites for ozone.

4.8.2. Linkage to Other Programs: Integration Beyond Traditional Networks

The clients of the SLT networks extend beyond the EPA Air Program Office and their immediate grantee organizations. For this Strategy to be truly national and sincere to optimization principles, there must be extended integration with other major networks and related national objectives. This integration should extend to:

- **Global/continental air quality issues**, including cross-continental transport of ozone, PM, and their precursors, persistent HAPs, such as mercury, dioxins, and PCBs, and to characterize global warming gases (e.g., ozone, carbon dioxide), and radiative losses due to light reflecting and absorbing aerosols and gases. In addition, intra-continental transport issues related to fluxes across U.S./Canadian and Mexican/U.S. borders should be served as part of the Strategy. Consideration should be given to an additional set of monitoring stations placed at critical locations along the coasts and borders for these purposes. Collaboration with other organizations, particularly NOAA, is suggested.

- **Ecosystem and related assessments**. Several national level monitoring efforts are in place or in planning potential for bidirectional benefits (i.e., two networks benefiting each other through complementary and/or similar measurements). Examples include CASTNET and IMPROVE, where both networks are used for routine evaluation of AQSMs, and visibility (IMPROVE) and atmospheric program (CASTNET) assessments, which benefit from SLT networks operating light scattering and chemical speciation measurements. Current planning for a routine PBT monitoring strategy focused on mercury, dioxins, and PCBs benefits from the existing networks through AQSM evaluation, as emerging models link across most pollutant categories, and mercury characterization is influenced by other species such as ozone. Advantages of leveraging operator resources and sharing platform space should be encouraged.

- **Research and intensive field campaigns**. Many of the more probing or diagnostic level research programs that attempt to uncover the underlying physical/chemical dynamics of atmospheric processes or characterize the more elusive or difficult specific causative factors responsible for adverse health effects are national needs. While these programs may primarily be conducted through research organizations and universities, it is imperative that they are perceived as integral components of the entire arsenal of technical tools used to understand, solve and account for progress in air quality management. As the Strategy is integrated more completely with other research level efforts, the efforts of routine monitoring operations will reap an important side benefit of additional counsel on routine aspects of monitoring operations, a process that has worked successfully to date with the Clean Air Scientific Advisory Committee (CASAC) Particle Monitoring Subcommittee.

The following are recommended and ongoing actions for extended integration to these three needs:

- Subject the Strategy, and specifically NCore recommendations, to broader scientific review and engagement with other Federal agencies and industry. Four specific actions include:

  1) establishing a new CASAC subcommittee to review NCore and related measurement methodology issues. This action was initiated in February 2002. This subcommittee will evaluate the NCore plan and provide counsel on the most reasonable mix of core pollutants, measurement locations, and related topics;

  2) adding NCore to the interagency discussions on air monitoring conducted under the Committee for Environment and Natural Resources (CENR) Air Quality Research Subcommittee (AQRS). This action was initiated in February, 2002;

  3) adding NCore as an integral component to the National Research Council (NRC) EPA PM coordination project that strives to facilitate coordination across modeling, monitoring and emissions and research and program objectives. This action begant in March, 2002

  4) adding Ncore to the NARSTO agenda to initaite dialogue with industry, Canada, Mexico, as well other NARSTO entities (e.g., states, EPA, universities). This action started in April, 2002 during the NARSTO Executive assembly meeting.

- Foster greater integration with networks such as IMPROVE and CASTNET by utilizing a subset those platforms as NCore rural sites. Several specific tasks that attempt to identify, characterize, and harmonize measurement differences between IMPROVE and the $PM_{2.5}$ speciation network are underway through EPA studies by OAQPS, ORD and ORIA, and Regional Planning Organizations (RPOs) .IMPROVE monitors have been added to a subset of CASTNET sites thereby providing more integration across IMPROVE, CASTNET and $PM_{2.5}$ speciation sites. The “core” Level 2 measurements should be added to some number of existing CASTNET and IMPROVE sites to enhance rural coverage.

- Collaborate directly with those organizations with the appropriate expertise and mission statements (e.g., NOAA) to build global and continental level monitoring needs into the national design.

4.9. The Future of National Network Design

The NCore proposal presents a logical, yet inexpensive intermediate step toward implementing far more reaching and innovative approaches in monitoring. In reality, there are very few bold proposals in NCore, which really are more a series of necessary, pragmatic adjustments to our current networks. There must be an exploration of expanding the use of simplified and complex technologies into the system, including simple and inexpensive passive samplers that flood an area to fill important spatial gaps and support network design through evaluation of spatial analysis methods. Advanced optical technologies that characterize air quality over extended paths would be consistent with the emphasis on measuring "representative" air quality in response to national objectives. Can we do better than just "leveraging" existing networks and settling for a small number of comprehensive multi-pollutant sites? Or, should we build in a future design that is more directly need-based. How do we anticipate future needs? In one sense the NCore design is purposefully presented as a "minimum" to prevent stagnation and allow for accommodation of new needs and technologies.

The future vision for air monitoring should not be limited by the current state of knowledge and status quo. Rather, forward-thinking ideas, given the tremendous advancements in computers and micro-technologies, should be the foundation for future networks. The goal for air quality monitoring should be to provide the most comprehensive characterization of air quality over space (i.e., three dimensions), the time continuum, and physical/chemical properties. To reach that goal, the following principles should be associated with a more innovative future for air monitoring:

1. Multi-pollutant sites should be the standard rather than the exception. Air quality is complex and we need a far more comprehensive measurements approach to convey true ambient air characteristics.

2. New measurement technologies should be encouraged, developed, tested, and brought into the mainstream of monitoring network as quickly and effectively as possible. Recent examples include advances in miniature technologies that incorporate the near-equivalent of a continuous gas chromatograph housed on a microchip; the multiple chemical/physical (e.g., continuous aerosol chemistry and size characteristics) processing capabilities of single particle analyzers; the use of optical path instruments to sample representative volumes; and the expansion of remote satellite sensing capability.

3. Models and measurements need to be coupled dynamically to substantially improve our ability to guide air management programs. The geometric increases in computational capacity are now available to produce near-real-time output of predictive concentrations. This discussion on monitoring should be extended to incorporate modeling directly and in a manner analogous to the Four Dimensional Data Assimilation (FDDA) meteorological models where observed data

iteratively “nudge” predictive values closer to observations with the result being a detailed spatial output grounded on observations. The future of a system like AIRNow should evolve along the following lines:

- **current:** real-time view of ozone mapped data across most of the United States;

- **next 1- 5years** with NCore: real-time view of ozone and $PM_{2.5}$ mapped data and other Level 2 core pollutants at specific points;

- **next 5-10 years:** real-time view of complete spatial fields reflecting integrated observations/predictions for a list of pollutants outputted from models, combined with an analysis system integrating meteorological and satellite air quality data imagery with the capability of air quality forecasting over the entire nation.

4. Extend the current engineering design approach through a more idealized scientific approach, utilizing the outreach and integration and review process established (e.g., via CASAC, NARSTO, CENR). This will require an investment from, as well as to, the research community.

4.10 NCore Implementation Schedule

The following schedule outlines the key time periods during which NCore is expected to be implemented.

2002:

- Adjust NCore design, as appropriate based on public comment and scientific (e.g., CASAC) feedback
- Complete network assessments and recommendations for network changes to accommodate NCore design

2003:

- Determine Level 2 site locations
- Establish Level 3 NCore sites
- Establish some Level 2 NCore sites

2004-2005:

- Complete deployment of remaining Level 2 sites
- Establish and deploy Level 1 sites
- Complete development of future blueprint for “idealized” design and network structure
- Complete 3-year cycle local network assessments

2005-2010:

- Evaluate and/or expand NCore as per idealized design and resource constraints
- Complete 5-year national network assessment

4.11 Scientific Review

It is expected that there will be such a peer review, principally through the Clean Air Scientific Advisory Committee (CASAC) starting in Fall 2002. Additional input has been, and will continue to be, sought through numerous other opportunities, including: the Air Quality Research Subcommittee for Environment and Natural Resources, January 2002; NARTSO Executive Assembly Meeting, May 2002; PM Supersite Principal Investigator Meeting, June 2002; PM Health Centers Meeting, July 2002.

Initial review from EPA-ORD recognizes the national air monitoring networks as providing the critical long-term foundation to the scientific underpinning to both atmospheric sciences and health and exposure scientific research. These long-term monitoring networks have provided data to: support atmospheric dispersion and receptor type model development, evaluation, and application to help link or apportion pollution observed at a receptor back to its source; support NAAQS development; identify compliance and accountability, and support health and exposure studies. The scientific community supports the re-design of these networks from single pollutant purpose to multi-pollutant purpose, based on continuous monitors, that will address multiple objectives as described within this document. However, while this document represents an excellent beginning, there are still significant obstacles (resources – human and financial, and technology) that need to be overcome to fully meet the needs of the scientific community. However, this community also realizes that science is not the only objective of the proposed Strategy, that the obstacles are real and may not be able to be easily overcome in the near-term, and understands that these parameters might reduce the full usefulness of the data to the scientific community. A comprehensive review by different groups of scientists will of course maximize the cross link between the many objectives and further review by CASAC, NRC, and principal investigators of major air programs (e.g., Supersites Program, PM Health Centers) is strongly encouraged.

The scientific community will continue to provide recommendations and to interact with OAQPS and the States as details of the siting and measurements are refined. Specifically the health effects and exposure community are concerned with siting of both the multi-pollutant sites and removal of single pollutant sites that may have or will play key roles in future health studies. Atmospheric scientists and air quality modelers are interested in continued communications to further support the siting of regional and rural as well as urban site locations to further support work across the source-receptor-exposure paradigm. Sufficient resources are needed to maximize the usefulness of the re-designed networks across all objectives realizing that the limited number of sites is close to but not quit sufficient to meet the multiple needs of this strategy. Specific details of where additional resources are needed will be discussed through the review process. Finally, there is a critical need to fund the Level 1 sites that will provide long-term chemical and physical data about given geographical areas that cannot be obtained at more than a few (8-10) sites nationwide. The scientific community believes this is a critical area need and that their involvement is essential to the development of this part of the network.

4.12 Resource Implications

The working assumptions for NCore are based on protecting and even enhancing the degree of flexibility SLTs have in conducting monitoring to meet their identified needs. It is anticipated that there are some very moderate resources to be allocated to NCore that will emerge from the network assessments that indicate reductions of traditional criteria pollutant monitoring sites. The development of NCore will also capitalize on resources available for special programs, such as PAMS and $PM_{2.5}$ speciation. It is further anticipated, though, that certain components of NCore will need additional funding initiatives because the divestment from existing programs is not sufficient to completely meet all the investment needs. Therefore, two very important implementation tasks need to be followed. First, as described above, maximum leveraging and optimization of existing networks must drive the initial implementation of NCore over the next one to five years. This includes strong encouragement, or perhaps requirement through regulations, to integrate the new air toxics trend sites into NCore. Second, modest investments from EPA must be contributed to catalyze NCore.
Those costs, which are expected to be covered by network adjustment resource savings, include the establishment, operation, and maintenance of all Level 2 and Level 3 sites (with the exception of new equipment capital costs), and all local/flexible sites.

Those costs, for which additional targeted resources are needed, have not been fully defined, but are estimated in the following list:

<u>Level 2 enhancements</u>

1. Purchase of equipment (including supporting QC calibration systems):
    - High-sensitivity CO, SO_2 and NO/NOy instruments ($5 million)
    - Continuous PM instruments ($2 million)
2. Monitoring platform enhancements (e.g., space, power) ($2 million)
3. Installation of information transfer technology hardware and software and data base expansion and incorporation of continuous Level 2 and Level 3 data into AIRNow. ($2 million).

Level 1

Level 1 sites are an integral component of NCore that strongly reflects the themes of insightful measurements and new technologies underlying the Strategy. Unfortunately, currently there appears to be no clear funding source to support these "transitional" sites, as standard resource pools historically have been associated with routine operations (e.g., Federal 103 and 105 Grants) or relatively open-ended research Grants to Universities for new methods development and testing. Clearly, strong consensus support must be developed for Level 1 sites to drive a funding initiative. It is premature to detail a cost proposal for Level 1 sites as the scope of operations is very loosely defined. For budget estimation needs, we will assume that a minimum of $2-3M per year is required for Level 1 operations and analysis as well as an initial $4M in capital expenses.

Thus the total additional costs to implement NCore are estimated at $15 million, one-time expense; and $2 million recurring annual operating expenses (Level 1) .

Speciation 'Trends' Sites

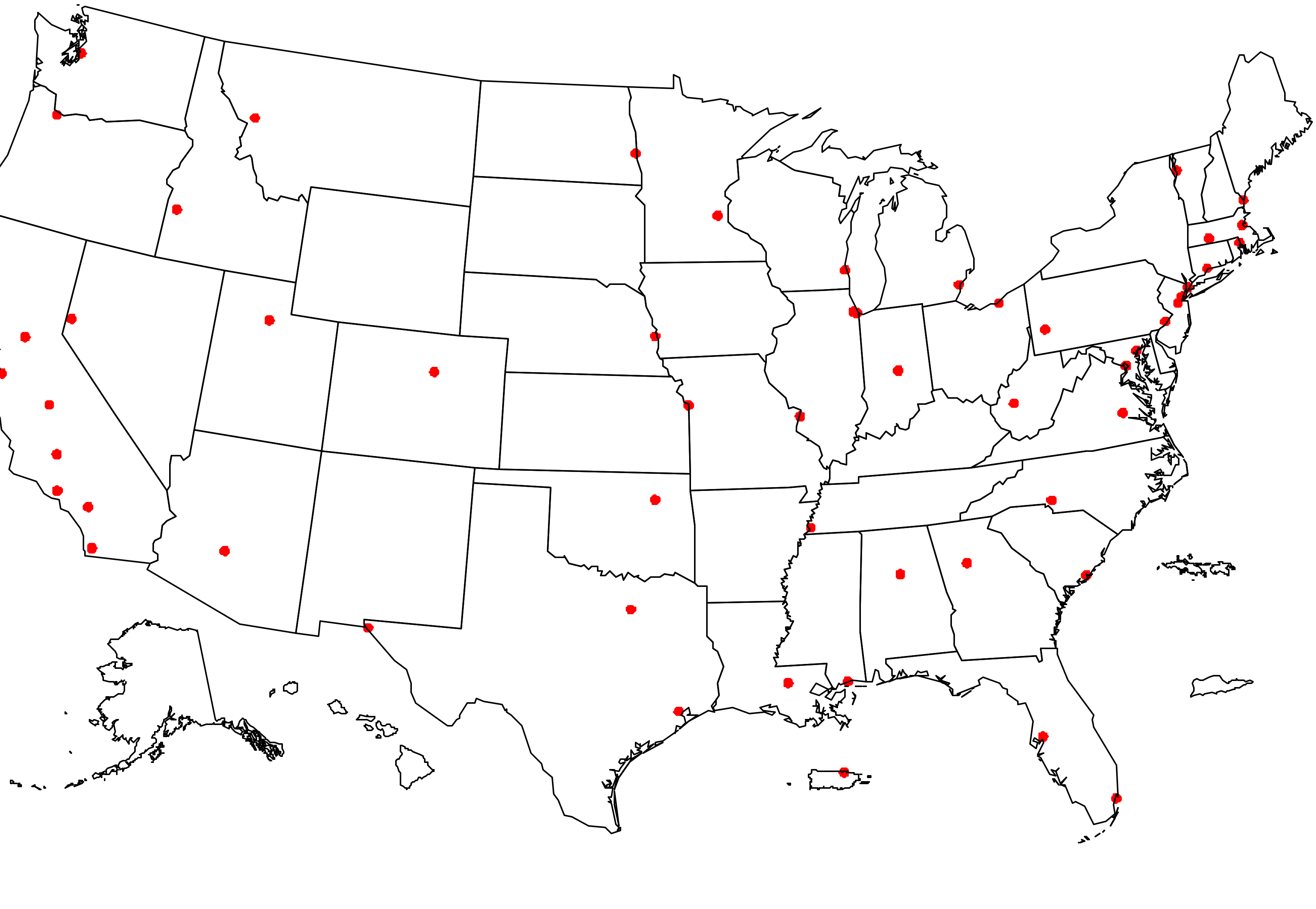
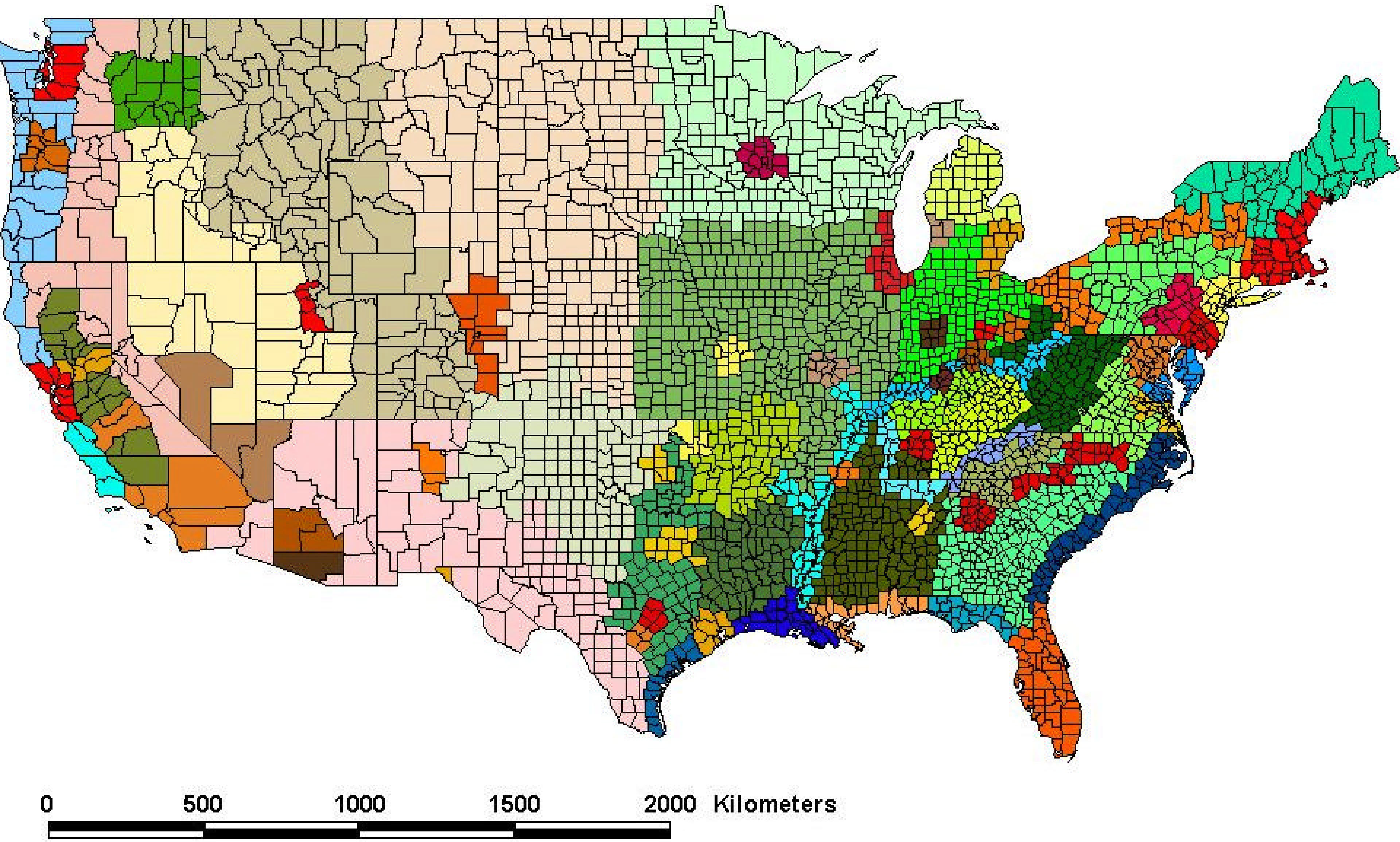
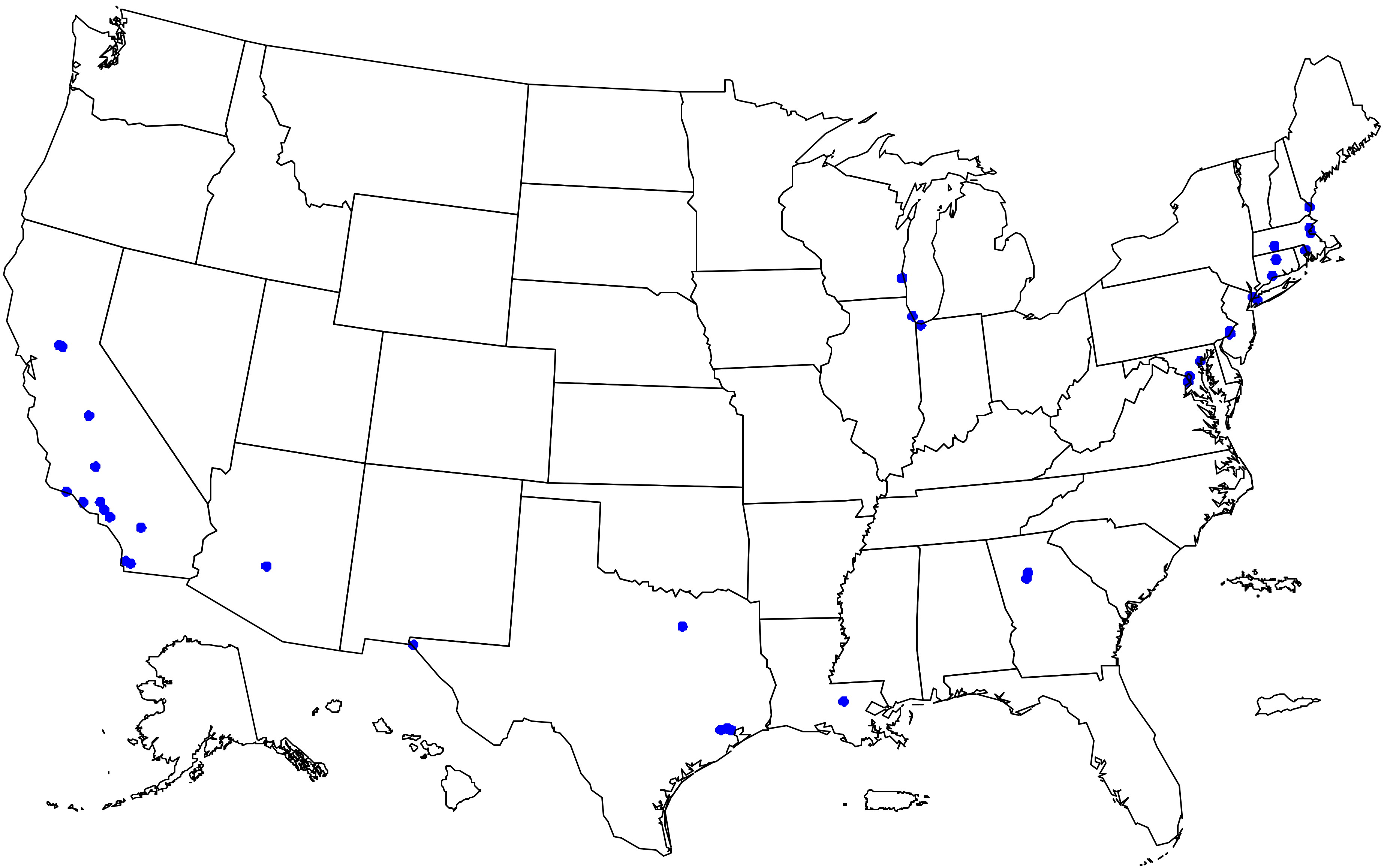


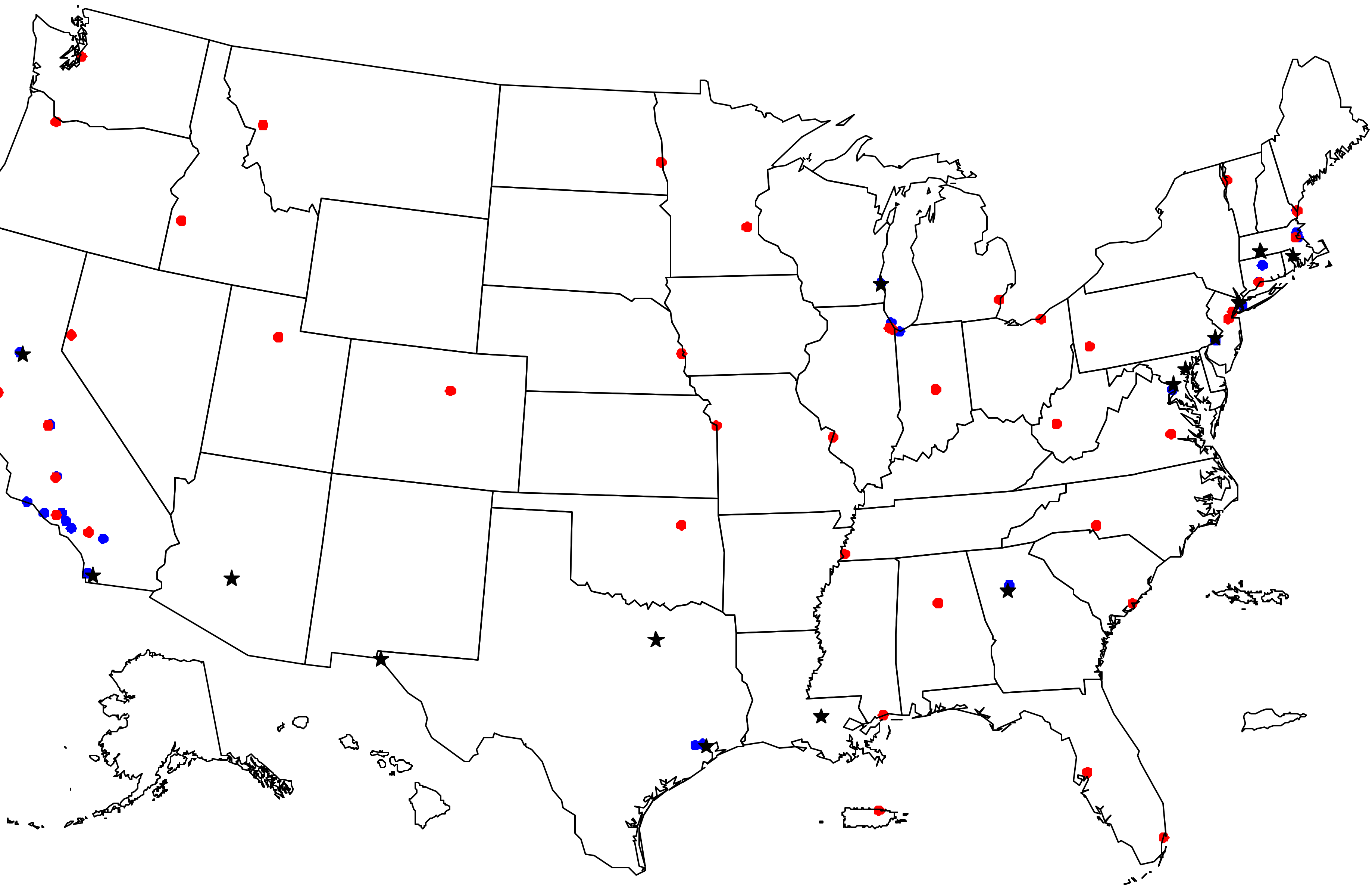
Figure 1: Population-based Air Quality Regions



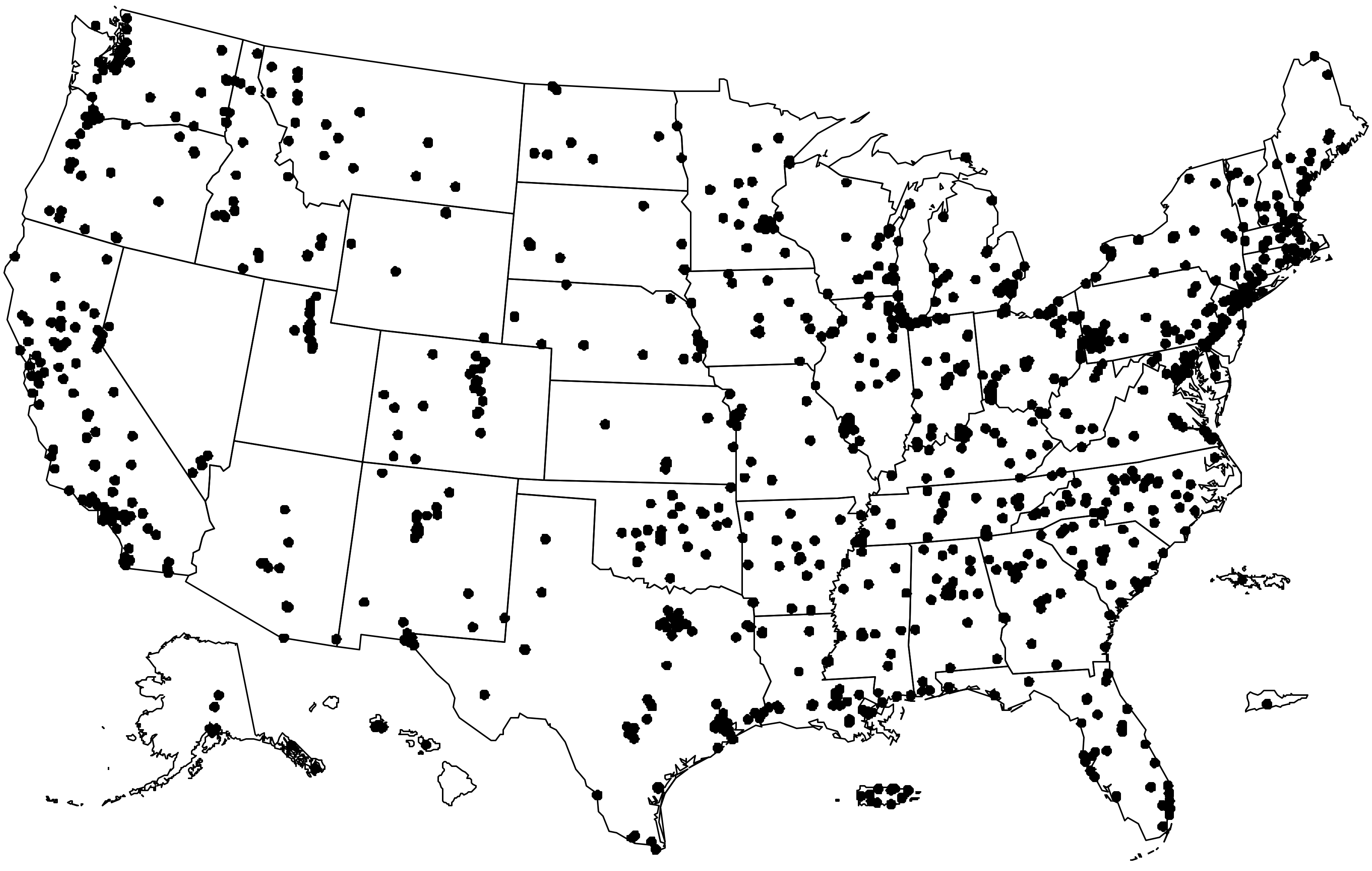
PAMS 'Type 2' Sites



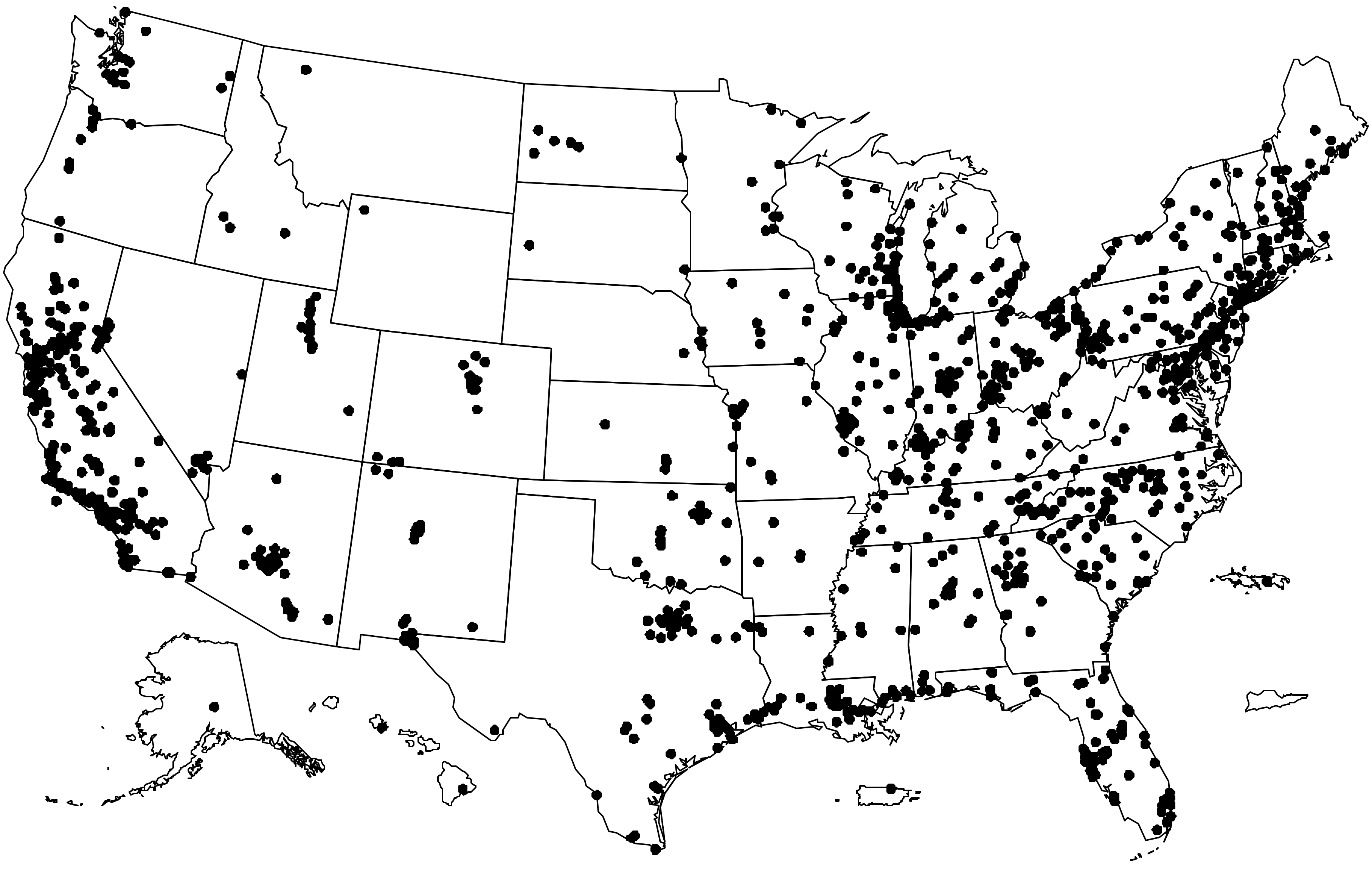
Speciation 'Trends' & PAMS 'Type 2' Sites



PM2.5 Sites

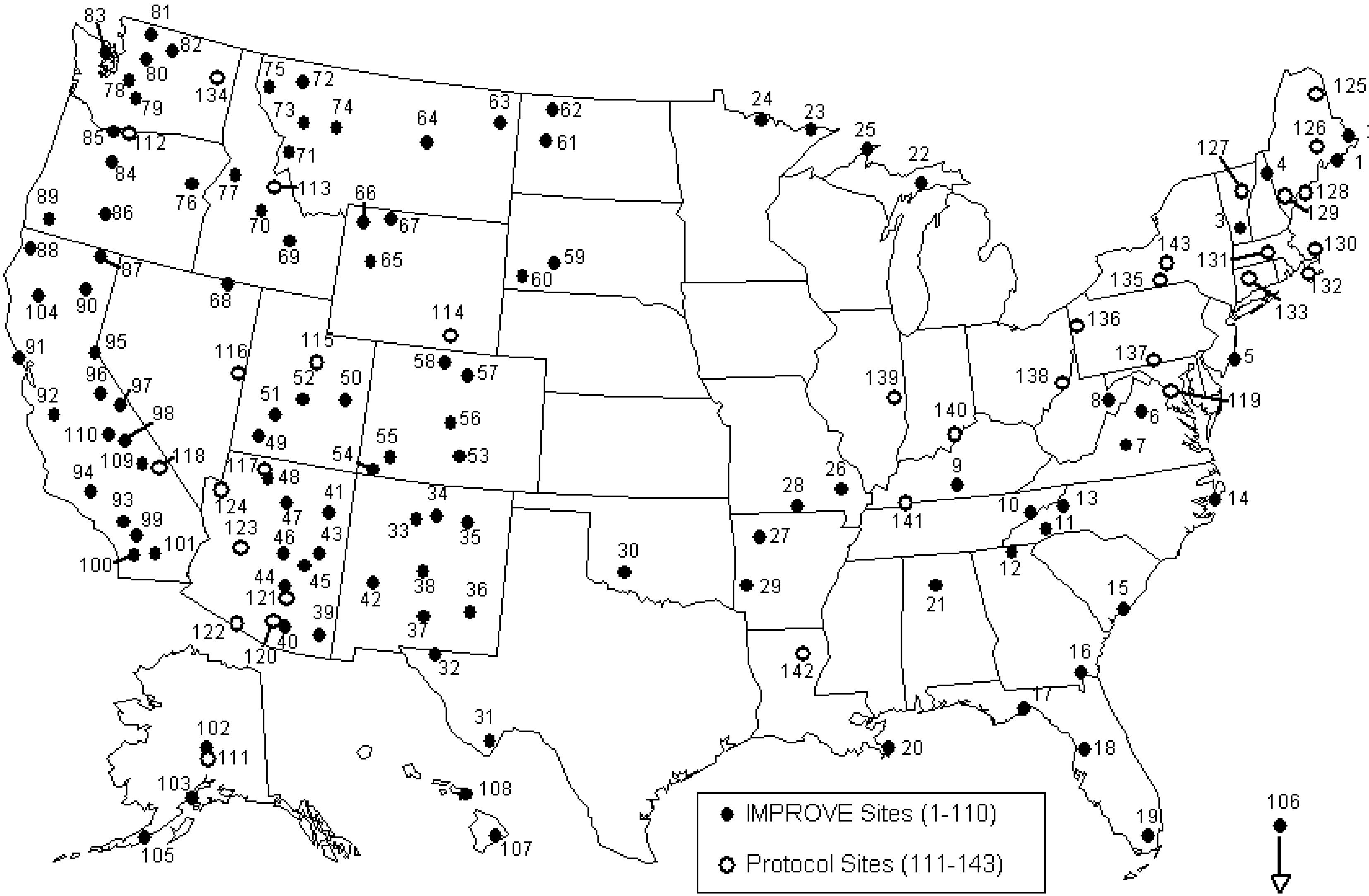


Ozone Sites

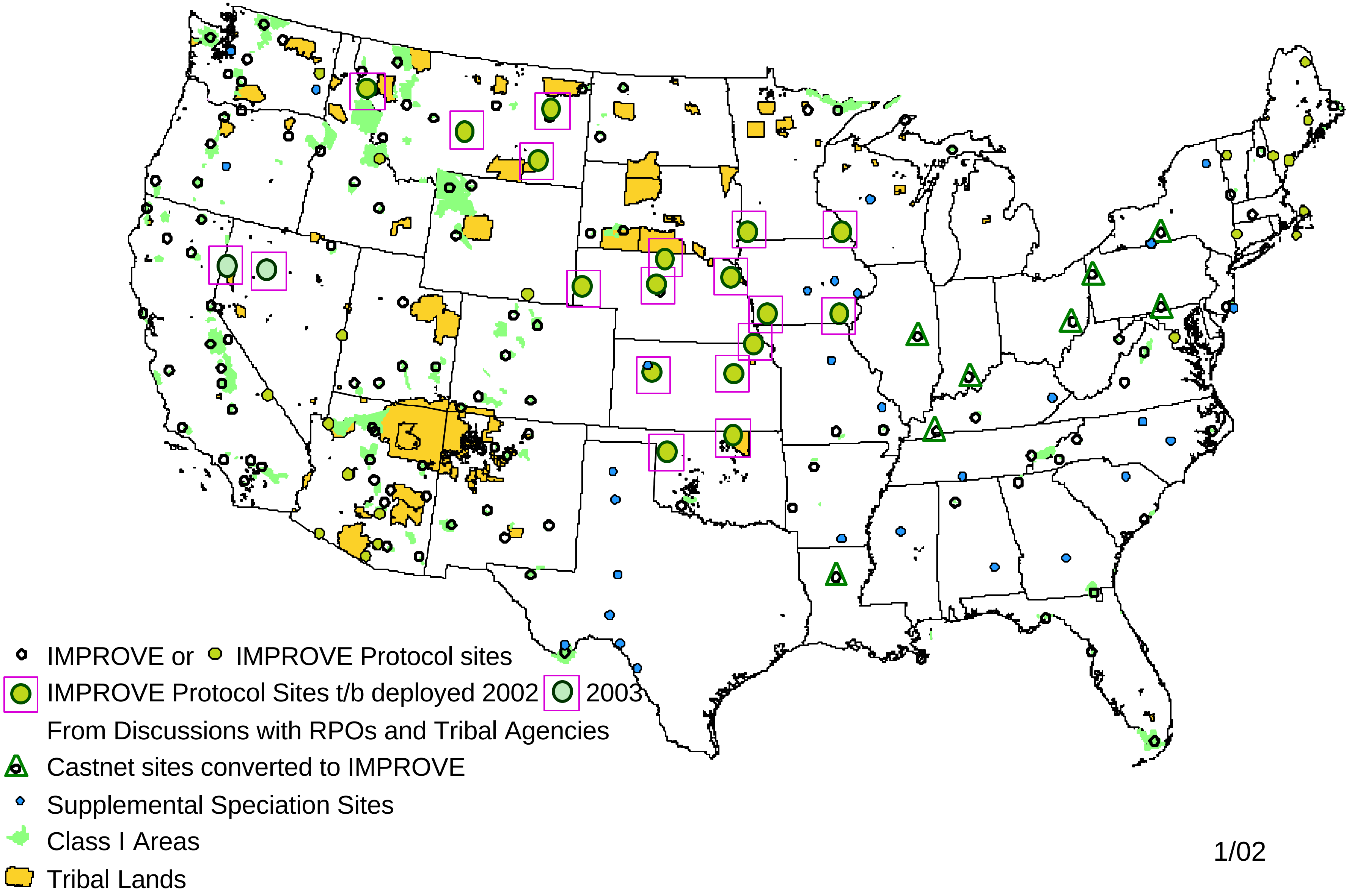


CASTNet Sites

IMPROVE (rural sites)



Current/Planned IMPROVE, IMPROVE Protocol & Rural Supplemental $PM_{2.5}$ Speciation Sites



Air Quality Monitoring in Support of Epidemiology

Lucas M. Neas

ORD / NHEERL / HSD / EBB

December 31, 2001

Air Quality Monitoring in Support of Epidemiology

Epidemiologic studies of the health effects of ambient particulate matter have been enormously important in determining the real health effects of real-world exposures to ambient particulate matter and co-pollutants among real human populations with the relevant range of variations in sensitivity. While some studies have generated their own air quality monitoring data, many epidemiologic studies have relied entirely on routinely collected air quality data supplied by a compliance-oriented air quality monitoring system. The health-based nature of the current air quality standards for particulate matter suggest a strengthening of this link between epidemiologic studies and compliance-oriented air quality monitoring systems.

By analogy, police officers are required to do more than simply find and arrest the bad guys. Police officers are expected to be on the watch for hazardous situations, such as adverse road conditions (exposure assessment); to assist citizens by summoning emergency services (health assessment); and to be particularly active in situations where these two conditions coincide, such as a hurricane warning (risk assessment and communication). Compliance-oriented air quality monitoring systems should also be designed to maximize their utility for these ancillary functions.

The choices involved in the determination of routine air quality monitoring systems will have important consequences for future epidemiologic research, for future risk assessments and for future regulation. The early choice of a 2.5 micron cut-point for fine particulate matter by research scientists has had important and unforeseen consequences for the air quality standard. The decisions now being made regarding compliance-oriented air quality monitoring systems will shape future epidemiologic research. For example, if the proposed air quality monitoring system cannot distinguish between the source contributions of gasoline and diesel vehicles, then many future epidemiologic studies will not be capable of making any distinction between these sources.

Types of Epidemiologic Studies

Various non-epidemiologists have complained about the inability of epidemiologists to clearly indicate their needs for air quality monitoring systems. Each epidemiologist seems to be describing an entire different set of research requirements. This apparent lack of consensus among epidemiologists is primarily a reflection of the differing exposure assessment requirements of different epidemiologic study types.

Epidemiologic studies of the health effects of ambient particulate matter fall into several distinct study types. Each type of study requires air quality data over different frequencies of measurement, different durations of measurement, different levels of geographic scope, and different levels of geographic detail. These epidemiologic studies fall into four broad categories: unenumerated open-cohorts ("time-series studies"), prospective closed-cohorts with repeated measurements, closed-cohorts analyzed for the timing of a health event ("case-crossover studies") and closed-cohorts analyzed for survival.

Unenumerated open-cohorts

Epidemiologic studies of unenumerated open-cohorts have played a key role in identifying fine particulate matter as an important public health problem. Since mortality and hospitalization records are routinely collected by public health authorities, these studies only require the addition of routinely collected daily data on weather and on ambient concentrations of particulate matter and co-pollutants. These studies have been conducted throughout the world under a large number of climatic conditions and sources of particulate matter.

The sample size of these studies is generally one or more well-defined urban areas each with a population of 100,000 or more persons followed over years of daily observations. While early studies were limited to single cities, the most extensive study was Jon Samet and colleagues' analysis of 90 U.S. cities (1). These 90 cities covered a broad range of city sizes: 3 cities were over 5 million, 20 cities were between 1 and 5 million, 35 cities were between ½ and 1 million, and 32 cities were under ½ million population. With the increase in the number of cities considered in a single study, researchers have gained an ability to examine the determinants of city-to-city variability in the exposure-response relationship.

The <u>frequency</u> of air quality measurements required for these studies depends on the time resolution of the health data. Since mortality and hospitalization data is available as daily counts, the ambient air quality measurements should be conducted at least daily at fixed locations with a minimum of missing data. The timing of missing air quality values must not be related to both air quality levels and health effects. Even routine one-in-six or one-in-three day sampling introduces an unacceptable pattern of missing values into the data and severely limits the analysis of the delayed (or lagged) health effects of particulate matter.

The <u>duration</u> of air quality measurements required for these studies depends on the size of the observed population and the natural variability of air quality levels. For most populations in a single urban area, air quality measurements must be continued for extensive periods of time (years or decades) in order to gain sufficient statistical power in terms of person-time of observation. However, a national network of monitoring stations representing the exposures of large numbers of individuals combined with daily source apportionment might be able to generate annual reports on the relative toxicity of different sources of particulate matter.

The <u>geographic scope</u> of air quality measurements required for these studies depends on the geographic scope of the health data system. While the scope of a hospital-based record system is limited by the size of the individual hospital's catchment area, mortality records and federally-assisted hospital care records are national in scope. A more extensive air quality monitoring network will (a) increase the total size of the population under study, (b) increase the number of study cities, (c) increase the statistical power to detect the relative health effects of various pollutants, (d) increase the ability of the study to understand the effects of various combination, and (e) increase the ability of the study to examine effect modifiers such as personal characteristics, behaviors, and situations, such as age, preexisting conditions, smoking status, and air conditioning. A nation-wide air quality monitoring system that captures the day-to-day variability in air quality levels for the entire U.S. population would permit an extension of these studies.

The geographic detail of air quality measurements required for these studies depends on the small-scale spacial variability of the pollutant under study and the geographic detail of the health data. Due to privacy concerns, health data are generally not available at less than the county or city level. Fortunately for these studies, the exposure data do not need to reflect the mean exposure of specific individuals or their total exposures to ambient and non-ambient particulate matter. The exposure data must only capture the day-to-day variability in ambient air quality levels for the population as a whole. Methodological issues concerning the use of a single central-site monitor to represent the exposures to particulate matter over broad geographic areas have been largely resolved by recent exposure assessment research.

Prospective closed-cohorts with repeated measurements

Epidemiologic studies of prospective closed-cohorts with repeated measurements of symptoms and physiological parameters ("panel studies") in both field and clinical settings have been instrumental in developing our understanding of the biologically plausible modes of action for particulate matter. By allowing each subject to serve as their own control, these studies have considerable statistical power to detect the determinants of the day-to-day variability of health. The physiological parameters have included pulmonary function (2), heart rate and heart rate variability (3), and biomarkers such as fibrinogen, C-reactive protein and plasma viscosity (4).

The sample sizes of these studies are generally of the order of 60 people followed three times each week for four- week periods, but a recent German study followed about 60 people monthly for an entire year. In the U.S., these studies tend to be of limited duration due to the costs of repeated measurements and subject boredom. However, both the National Cooperative Inner-City Asthma Study and the subsequent Inner-City Asthma Study used an interesting variant of this study design with rotating panels of study subjects each of whom were on study daily for two week periods spaced at six-month intervals (5). By dividing their subjects into 12 groups, the investigators were able to maintain a study of children under observation daily for 18 months.

The frequency of air quality measurements required for these studies depends on the time resolution of the health data. Since the timing of the health measurements is often under the control of the investigator, these studies have investigated the health effects of exposures one to four hours prior to the health examination. Continuous or hourly data on air quality will be of great utility to these studies.

The duration of air quality measurements required for these studies depends on the period of observation of the health effects. In most studies involving intensive physiologic measurements, the duration of observation is relatively brief, four to eight weeks. For the rotating panel design, the period of health observation was over 18 months. The air quality monitoring system should not be reduced in frequency or geographic detail during such studies.

The geographic scope of air quality measurements required for these studies depends on the geographic scope of the study population. These epidemiologic studies are general conducted with health measurements performed at a single location, but successful studies have been conducted with subjects scattered over a single community. As with the open-cohort studies, the exposure data must capture the short-term variability in air quality levels for the study population as a whole. The exposure data do not need to reflect the mean exposure of any individual or the total exposures to ambient and non-ambient particulate matter.

The geographic detail of air quality measurements required for these studies depends on the small-scale spacial variability of the pollutant under study. For pollutants with low small-scale variability, such as fine particulate matter, central site measurements generally are sufficient, while for pollutants with considerable small-scale variability, such as ultrafine particulate matter, air quality measurements should be conducted near to the location where the health measurements are performed or where the study subjects reside.

Closed-cohorts with timing of a health event

Epidemiologic studies of closed-cohorts based on the timing of a health event are generally distinguished from the prospective cohorts with repeated measures in that either a) the subjects are identified by the occurrence of a rare health event such as a myocardial infarction (6) or b) the health data is generated by the recording of a rare health event such as the discharge of an implanted cardiac device (7). In both cases, the analysis concerns the exact timing of the health event and proceeds using a case-crossover method.

While only a few epidemiologic studies have been conducted using this study design, the research potential of such studies is great. The clinical significance of either a myocardial infarct or a device discharge is obvious. Given that these are rare health events, these studies are generally conducted in a retrospective manner with the acquisition of exposure data from a routine monitoring system after the occurrence of the health event.

The frequency of air quality measurements for these studies depends on the time resolution of the health data which can be quite precise when recorded by an implanted cardiac device. While routine hospital data does not have sufficient time resolution, recent studies have relied on interviews with heart attack survivors to establish the timing of the onset of symptoms. Due to the significance of the cardiac event and the important of prompt care, the timing of the onset of symptoms is often well remembered by the survivor. Continuous or hourly data on air quality will be of great utility to these studies.

The duration of air quality measurements required for these studies depends on the need to collect a sufficient number of health events for analysis. Since the required time period can easily cover several years, a stable air quality monitoring system that can provide extensive historic data will greatly facilitate these studies.

The geographic scope of air quality measurements required for these studies depends on the geographic scope of the study population. While these studies generally are conducted in a few hospitals or a single clinical practice, the study subjects may come from relative large catchment areas encompassing entire urban areas. As with the open-cohort studies, the exposure data must capture the short-term variability in air quality levels for the study population as a whole. The exposure data do not need to reflect the mean exposure of any individual or the total exposures to ambient and non-ambient particulate matter.

The geographic detail of air quality measurements required for these studies depends on the small-scale spacial variability of the pollutant under study. For pollutants with low small-scale variability, such as fine particulate matter, central site measurements generally are sufficient. However, a recent study found that cardiac events were more strongly associated with nitrogen dioxide than with fine particles (7). This finding suggests that pollutants with greater small-scale variability, such as ultrafine particulate matter, may be producing this health effect. Furthermore, these studies should be capable of ascertaining the location of each study subject at the time of the event which would permit the use of very fine geographic detail on air quality.

Closed-cohorts analyzed for cumulative incidence (survival)

Epidemiologic studies of closed-cohorts analyzed for cumulative incidence of a health event over time have shown the most adverse effects of long-term exposures to particulate matter. In adult cohorts, these studies follow the survival of a well-characterized cohort of subjects in communities with differing long-term air quality exposures. In cross-sectional studies of children, these studies collect information on children's health status during the time preceding the survey.

The two major adult survival studies have been the Dockery and colleagues study of 8,111 adults followed for 14 to 16 years in six U.S. cities (8) and the Pope and colleagues study in 151 U.S. cities using the American Cancer Society cohort of 552,138 adults followed for nine years (9). While Dockery and colleagues' study in six U.S. cities was supported with research-oriented air quality monitoring, the Pope and colleague's study relied entirely on routine compliance-oriented air quality monitoring. Follow-up of these cohorts has continued through 2000 and will be continued as these cohorts advance in age.

Examples of the many children's cohorts include Harvard Six-Cities Studies (10), the Harvard 24-Cities Studies (11, 12), the Kanawha Valley Health Study (13), and the Southern California Children's Health Study (14, 15). The Harvard studies dealt with large-scale differences on long-term exposures across different communities, while the other two studies dealt with intra-urban gradients of air pollutants. In all cases, limited air quality monitoring was used to infer long-term exposure histories for these children.

The frequency of air quality measurements required for these studies are less intensive than for the other study types. Monthly averages should be sufficient for this type of study, so long as the measurements are sufficiently frequent to capture the average ambient air quality during the month. One-in-three day air quality monitoring may be sufficient, but one-in-six day monitoring may not be adequate for the calculation of monthly averages.

The duration of air quality measurements required for these studies is considerably more extensive than for the other study types. In order to adequately capture the long-term exposure history of study subjects, the air quality monitoring data must capture a considerable portion of their lifetime. The nine to 16 years of follow-up in the cited studies still required the assumption that the relative rankings of the cities with respect to air quality during the follow-up period correctly represented the relative rankings of long-term exposures for the subjects.

The geographic scope of air quality measurements required for these studies is also greater than for the other study types. Due to the high geographic mobility of the U.S. population, a single location cannot adequately represent many individuals' long-term exposures. A nation-wide air quality monitoring network that captures the ambient air quality exposures of a substantial portion of the U.S. population would be necessary for these studies.

The geographic detail of air quality measurements required for these studies needs to adequately characterize individuals' long-term exposures to ambient pollutants. Since healthy adults tend to travel around within their local communities, intra-community geographic detail may be less important for this type of study. However, given the broad, national scope proposed for such a study, regional geographic detail is very important. Increased geographic detail may be required for communities with local heavy industry and within a complex urban setting such as the U.S. Eastern Megalopolis. The most important requirement for this type of study is that the exposure assessment methods must be standardized across all monitoring locations. Variations in monitoring methods could result in false associations between health and air quality.

Epidemiologic study requirements for air quality monitoring

The requirements for air quality monitoring differ greatly across the various epidemiologic study designs (table 1). This table clarifies the differing requirements expressed by epidemiologists for routine air quality monitoring systems. The exposure assessment requirements for epidemiologic studies differ greatly according to the type of studies under consideration.

Table 1. Summary of air quality monitoring requirements by type of epidemiologic study.

	Unenumerated Open-Cohorts	Closed-Cohorts with repeated measures	Closed-Cohorts analyzed for event timing	Closed-Cohorts analyzed for cumulative incidence
Frequency	Daily	Hourly	Hourly	Monthly
Duration	Years to Decades	Weeks to Years	Years	Decades
Geo. Scope	Urban Centers	Limited	Urban Centers	U.S. Population
Geo. Detail	County	Study site	County	Regions

The maximum requirements for a comprehensive air quality monitoring system are clearly quite daunting: hourly data collected for decades to capture both the short-term and long-term exposures of populations ranging from a few study subjects to the U.S. population as a whole and from regional to neighborhood levels of detail.

Compliance-oriented air quality monitoring systems alone cannot fully meet the needs of epidemiologic studies. Research-oriented air quality monitoring and air quality models will be required to supplement the compliance-oriented systems. However, research-oriented air quality monitoring is an expensive and difficult component of prospective epidemiologic research. Epidemiologic research on the long-term exposures of adults requires the assessment of exposures over decades with a real premium on routine and geographically extensive compliance-oriented air quality monitoring systems.

Combination of monitoring and modeling

Environmental epidemiologists are accustomed to using limited environmental measurements in the context of a model. Often these models are very naive and simplistic, such as assuming that central site monitoring can well capture the ambient exposures of an extended population over a wide geographic area and that measurements conducted over limited periods can adequately capture past exposure gradients. Nevertheless, epidemiologic studies utilizing these simple models have been very successful in elucidating the health effects of environmental exposures. More sophisticated models have not always shown a clear advantage in statistical power over the simpler models, since model precision often comes at substantial cost and a reduced sample size. However, by using appropriate air quality models and geographic information systems, a compliance-oriented air quality monitoring system with limited direct measurements could be used to provide more intensive research data.

The <u>frequency</u> and <u>geographic detail</u> do not need to be the same for each air quality monitoring parameter. Since many parameters are highly correlated, air quality models may allow the imputation of values across different levels of frequency and geographic detail. For example, a temporal air quality model could permit the pairing of (a) a device measuring hourly light scattering or beta-emission attenuation that provides a high-frequency estimate of $PM_{2.5}$ with (b) a lower-frequency (24-hour), but more accurate gravimetric measurement of $PM_{2.5}$. Similarly, a spatial air quality model could permit the imputation of exposures to ultra-fine particulate matter from (a) costly ultra-fine measurements at a few locations, (b) co-pollutants measured at more locations with greater geographic detail, and (c) distance to and traffic density on nearby roadways. Spatial air quality models may also permit measurements of specific pollutants conducted at differing locations to be integrated into a common model.

The interaction between geographic scope and geographic detail is particularly relevant for the assessment of long-term exposures. A nation-wide system for exposure assessment (scope) will require the identification of a sufficiently large number of geographic regions so that long-term average air quality levels are relatively uniform across the area (detail). An illustrative attempt at the delineation of population regions across the U.S. is included as Appendix A. For some study designs, these regional averages could be supplemented by information on the subject's residential location with the study region.

Geographic information systems have great potential for application to these problems. In principle, the residential location of most study subjects may be ascertained to specific street addresses which may be mapped to census and traffic engineering data. Data from the U.S. Decennial Census can provide information on neighborhood characteristics including population density and type of housing. Routinely collected traffic engineering data can provide the location of major highways and traffic density for most urban areas. In addition to this information on these mobile and area sources, the locations and emissions of point sources would complete the source profile. The locations of and data from compliance-oriented air quality monitoring stations would complete the geographic information system.

The precision required for a national air quality exposure assessment system should be defined in terms of the relative error for specific proportions of the U.S. population. A small proportion (less than 1 percent) of the study population could have their exposures greatly misclassified (greater than 20 percent) without introducing a important bias into an epidemiologic study, provided that the exposure misclassification was unrelated to their health status after adjustment for age and other measurable characteristics.

Conclusions

Compliance-oriented air quality monitoring has played and will continue to play a major role in determining the ability of epidemiologists to assess the health effects of ambient pollutants. Any new system should be national in scope with carefully standardized measurements, with an ability to provide hourly data and monthly averages, and with sufficient geographic detail to permit accurate community-level exposure estimates. The monitoring system must be coupled with a research-oriented modeling system that will permit increased time and spatial resolution for less frequent and more widely spaced monitors.

References

1. Samet JM, Zeger SL, Dominici F, Curriero F, Coursac I, Dockery DW, Schwartz J, Zanobetti A. The National Morbidity, Mortality, and Air Pollution Study. Part II: Morbidity and mortality from air pollution in the United States. Res Rep Health Eff Inst 2000 Jun;94(Pt 2):5-70.

2. Neas LM, Dockery DW, Koutrakis P, Tollerud DJ, Speizer FE. The association of ambient air pollution with twice daily peak expiratory flow rate measurements in children. Am J Epidemiol 1995 Jan 15;141(2):111-22.

3. Creason J, Neas L, Walsh D, Williams R, Sheldon L, Liao D, Shy C. Particulate matter and heart rate variability among elderly retirees: the Baltimore 1998 PM study. J Expo Anal Environ Epidemiol 2001 Mar-Apr;11(2):116-22.

4. Peters A, Frohlich M, Doring A, Immervoll T, Wichmann HE, Hutchinson WL, Pepys MB, Koenig W. Particulate air pollution is associated with an acute phase response in men; results from the MONICA-Augsburg Study. Eur Heart J 2001 Jul;22(14):1198-204.

5. Mortimer KM, Tager IB, Dockery DW, Neas LM, Redline S. The effect of ozone on inner-city children with asthma: identification of susceptible subgroups. Am J Respir Crit Care Med 2000 Nov;162(5):1838-45

6. Peters A, Dockery DW, Muller JE, Mittleman MA. Increased particulate air pollution and the triggering of myocardial infarction. Circulation 2001 Jun 12;103(23):2810-5.

7. Peters A, Liu E, Verrier RL, Schwartz J, Gold DR, Mittleman M, Baliff J, Oh JA, Allen G, Monahan K, Dockery DW. Air pollution and incidence of cardiac arrhythmia. Epidemiology 2000 Jan;11(1):11-7

8. Dockery DW, Pope CA 3rd, Xu X, Spengler JD, Ware JH, Fay ME, Ferris BG Jr, Speizer FE. An association between air pollution and mortality in six U.S. cities. N Engl J Med 1993 Dec 9;329(24):1753-9.

9. Pope CA 3rd, Thun MJ, Namboodiri MM, Dockery DW, Evans JS, Speizer FE, Heath CW Jr. Particulate air pollution as a predictor of mortality in a prospective study of U.S. adults. Am J Respir Crit Care Med 1995 Mar;151(3 Pt 1):669-74

10. Dockery DW, Speizer FE, Stram DO, Ware JH, Spengler JD, Ferris BG Jr. Effects of inhalable particles on respiratory health of children. Am Rev Respir Dis 1989; 139:587-594.

11. Dockery DW, Cunningham J, Damokosh AI, Neas LM, Spengler JD, Koutrakis P, Ware JH, Raizenne M, Speizer FE. Health effects of acid aersols on North American children: respiratory symptoms. Environ Health Perspect 1996; 104:500-505.

12. Raizenne M, Neas LM, Damokosh AI, Dockery DW, Spengler JD, Koutrakis P, Ware JH, Speizer FE. Health effects of acid aerosols on North american children: pulmonary function. Environ Health Perspect 1996; 104:506-514.

13. Ware JH, Spengler JD, Neas LM, Samet JM, Wagner GR, Coultas D, Ozkaynak H, Schwab M. Respiratory and irritant health effects of ambient volatile organic compounds: the Kanaha County Health Study. Am J Epidemiol 1993; 137:1287-1301.

14. Peters JM, Avol E, Navidi W, London SJ, Gauderman WJ, Lurmann F, Linn WS, Margolis H, Rappaport E, Gong H, Thomas DC. A study of twelve Southern California communities with differing levels and types of air pollution. I. Prevalence of respiratory morbidity. Am J Respir Crit Care Med 1999 Mar;159(3):760-7.

15. Peters JM, Avol E, Gauderman WJ, Linn WS, Navidi W, London SJ, Margolis H, Rappaport E, Vora H, Gong H Jr, Thomas DC. A study of twelve Southern California communities with differing levels and types of air pollution. II. Effects on pulmonary function. Am J Respir Crit Care Med 1999 Mar;159(3):768-75

Air Quality Monitoring in Support of Epidemiology

Appendix A:

Population-based Air Quality Regions

Lucas M. Neas

ORD / NHEERL / HSD / EBB

December 31, 2001

Appendix A: Population-based Air Quality Regions

The 281,421,906 residents of the United States (April 1, 2000) are unevenly spread over an area of 9,628,382 square kilometers (km^2) divided by civil jurisdictions into 3,111 counties and equivalent entities. No air quality monitoring network can fully capture the ambient air concentrations of criteria air pollutants in the vicinity of their 105,480,101 occupied housing units. This problem of air quality exposure assessment for the U.S. population can be reduced to a more manageable scope by a geographic information system that combines direct monitoring at a comprehensive network of air quality monitoring stations with sophisticated models. As an aid to this process, the entire area of the U.S. must be divided into a limited number of smaller, more tractable air quality regions. This document is an initial attempt at a population-based approach to the designation of air quality regions.

The densest concentrations of the U.S. population are found in 253 Metropolitan Statistical Areas (MSA) and 19 Consolidated Metropolitan Statistical Areas (CMSA) designated and maintained by the White House Office of Management and Budget (OMB) in the Federal Information Processing Standard (FIPS) 8-6. The 19 CMSA's are divided into 76 Primary Metropolitan Statistical Areas (PMSA). These MSA's/CMSA's range in population from the 21,119,865 residents of the New York–Northern New Jersey–Long Island, NY–NJ–CT–PA CMSA to the 57,813 residents of the Enid, OK MSA and contain 81 percent of the U.S. resident population. The MSA's and the non-metropolitan counties and equivalent entities form the elemental units of the designated air quality regions. In several policy statements, OMB has indicated that all Federal Agencies should utilize these MSA's. These designated air quality regions are therefore aggregates of well-defined statistical entities.

For the purposes of designating air quality regions, this process of aggregation from MSA's does lead to certain unusual features on a map. For example, the county of San Bernardino, CA is part of the Los Angeles–Riverside–Orange County, CA CMSA even though much of the county's area lies east of the Sierra Nevada mountains. The central point for the weighted population distribution within San Bernardino (the population centroid) lies near the western edge of the county. The overwhelming majority of the residents of San Bernardino county are properly characterized by their inclusion in the Los Angeles–Riverside–Orange County, CA CMSA.

The current version of these air quality regions (figure 1) does not cover Alaska (626,932 residents) or Hawaii (1,211,537 residents). The Commonwealth of Puerto Rico is not included in the U.S. population totals or in the current air quality regions. In future versions, Alaska probably should be divided into two or more air quality regions, while Hawaii and Puerto Rico probably should be single air quality regions.

Air Quality Considerations

These population-based air quality regions have been assembled with a basic knowledge of the general determinants and levels of criteria air pollutants, but not on the basis of specific air quality measurements. In each region, air quality sources will be a combination of (a) the long-range transport of primary and second pollutants, (b) the atmospheric generation of secondary pollutants from transported and locally-generated primary pollutants, (c) area sources, (d) local mobile sources, and (e) local point sources. The first two source categories will result in regional-scale increases in air pollutant concentrations, while population-exposures to air pollutants from the other three source categories may be more greatly affected by proximity to the source.

Ideally, each air quality region should be small enough so that the region's population experiences similar exposures to the regional-scale sources of air pollution. However, considerable variations may still exist in population exposures to air pollutants from local sources. Air quality regions that would be small enough to ensure complete uniformity of population exposures to pollutants from all sources would be too numerous to permit the development of a workable exposure assessment system.

The exposure of the air quality region's residents to regional-scale exposures to air pollutants may be determined from direct monitoring. The determination of population exposures to local sources, such as mobile sources, will require a combination of direct monitoring and modeling. The air quality models will need to take into consideration each resident's proximity to major roadways, the density and type of traffic on these roadways, and the density of smaller roadways in the neighborhood. These small-scale considerations may be more important in air quality regions with considerable variation in the density of population, housing units, and roadways.

Types of Air Quality Regions

The 23 **major urban regions** consist of one or more undivided MSA's or CMSA's. These major urban areas range in size from the 21,104,292 residents of the New York City air quality region to the 2,566,053 residents of the Richmond to Norfolk air quality region. In a few instances, one or more adjoining non-MSA counties have been included to preserve the contiguous nature of these major urban areas. The combined populations of these 23 major urban regions (139,682,947 residents) is nearly half of the entire U.S. population.

The 21 **city regions** consist of MSA's with populations between 750,000 and 2,500,000 residents that are not part of larger urban areas. A few of the small MSA's within the following rural regions may deserve promotion to city areas if local conditions warrant their increased monitoring. An example of such a city is the El Paso, TX MSA that is located just north of the major Mexican city of Ciudad Juarez (over 2,000,000 residents). The combined populations of these 21 city regions (23,392,084 residents) is eight percent of the U.S. population.

The 17 **rural regions** consist of less urban counties and equivalent entities, but may include isolated MSA's of less than 750,000 residents. The designation of these rural regions followed to general boundaries of the State Economic Areas delineated by the U.S. Bureau of the Census in the 1950's. The Appalachian rural regions follow the boundaries established by the Appalachian Regional Commission, but this region was divided into five air quality regions to allow for regional-scale differences in air pollutant concentrations. These rural regions contain small MSA's which are listed in the definition of each region.

The 4 **valley regions** consist of rural regions along major waterways in the eastern U.S. Historically, narrow river valleys have been a major factor in locally high air pollutant concentrations and in major air pollution disasters such as occurred in Denora, PA. These valley regions may include isolated MSA's of less than 1,000,000 residents.

The 7 **coastal regions** consist of counties within 10 km of the coast lines of the U.S. and outside the major urban areas. Unlikely narrow river valleys, coastal regions have generally low air pollutant concentrations due to on and off shore breezes and other routine meteorological conditions. The major urban areas of the northeastern U.S., Houston, TX and Pensacola to New Orleans are not included as coastal regions.

The 7 **extremely low-density regions** consist of rural regions with population densities less than 7 residents per km^2. Due to the low population density, air quality monitoring is a very inefficient means of estimating population exposures. Fortunately, air pollutant concentrations tend to be very low in these regions. Only four of the MSA's in these low-density regions have more than 240,000 residents: the Albuquerque, NM MSA (712,738 residents); the Boise City, ID MSA (432,345 residents); the Reno, NV MSA (339,486 residents); and the Lubbock, TX MSA (242,628 residents).

Major Urban Regions

The **New York City** air quality region (21,104,292 residents) consists of the New York–Northern New Jersey–Long Island, NY–NJ–CT–PA CMSA excluding Litchfield county, CT (26,829 km^2 with 787 residents per km^2). This CMSA includes the following 15 PMSA's: Trenton, NJ (350,761 residents); Bergen–Passaic, NJ (1,373,167 residents); Jersey City, NJ (608,975 residents); Middlesex–Somerset–Hunterdon, NJ (1,169,641 residents); Monmouth–Ocean, NJ (1,126,217 residents); Newark, NJ (2,032,989 residents); New York, NY (9,314,235 residents); Newburgh, NY–PA (387,669 residents); Dutchess County, NY (280,150 residents); Nassau–Suffolk, NY (2,753,913 residents); New Haven–Meriden, CT (542,149 residents); Stamford–Norwalk, CT (353,556 residents); Bridgeport, CT (459,479 residents); Danbury, CT (183,303 residents in Fairfield county); and Waterbury, CT (187,200 residents in New Haven county). In order to preserve county boundaries in the New England area, this region does not include any portion of Litchfield county, CT: 34,677 residents of the Danbury, CT MSA and 41,784 residents of the Waterbury, CT MSA.

The **Washington/Baltimore** air quality region (7,608,070 residents) consists of the Washington–Baltimore, DC–MD–VA–WV CMSA (24,825 km^2 with 307 residents per km^2). This CMSA includes the Baltimore, MD PMSA (2,552,994 residents), the Washington, DC–MD–VA–WV PMSA (4,923,153 residents) and the Hagerstown, MD PMSA (131,923 residents).

The **Philadelphia** air quality region (6,188,463 residents) consists of the Philadelphia–Wilmington–Atlantic City, PA–NJ–DE–MD CMSA (15,483 km^2 with 400 residents per km^2). This CMSA includes the Atlantic–Cape May, NJ PMSA (354,878 residents), the Philadelphia, PA–NJ PMSA (5,100,931 residents), the Vineland–Millville–Bridgeton, NJ PMSA (146,438 residents), and the Wilmington–Newark, DE–MD, PMSA (586,216 residents).

The **Boston/Providence/Hartford** air quality region (10,320,465 residents) consists of 31 counties along the Atlantic coast from Hartford, CT to Portland, ME (43,225 km^2 with 239 residents per km^2) including the Boston–Worcester–Lawrence, MA–NH–ME–CT CMSA. The Boston–Worcester–Lawrence, MA–NH–ME–CT CMSA includes the following 10 PMSA's: Boston, MA–NH (3,406,829 residents); Brockton, MA (255,459 residents); Fitchburg–Leominster, MA (142,284 residents); Lawrence, MA–NH (396,230 residents); Lowell, MA–NH (301,686 residents); Manchester, NH (198,378 residents); Nashua, NH (190,949 residents); New Bedford, MA (175,198 residents); Portsmouth–Rochester, NH–ME (240,698 residents); and Worcester, MA–CT (511,389 residents). Six smaller MSA's that lie north of the New York City region have been joined into this air quality region including the Providence–Fall River–Warwick, RI–MA MSA (1,188,613 residents), the Hartford, CT MSA (1,183,110 residents), the New London–Norwich, CT–RI MSA (293,566 residents), the Springfield, MA MSA (591,932 residents), the Barnstable–Yarmouth, MA MSA (162,582 residents), and the Portland, ME MSA (243,537 residents). In order to preserve county boundaries in the New England area, the borders of these MSA's and PMSA's have been expanded to include the non-MSA portions of the counties in which they lie. Thus, this region includes all of Litchfield county, CT: 34,677 residents of the Danbury, CT PMSA and 41,784 residents of the Waterbury, CT PMSA.

The **Albany to Niagra** air quality region (4,435,206 residents) consists of a band of seven MSA's running west from the Pittsfield, MA area to the Niagra Falls, NY area (43,315 km^2 with 102 residents per km^2). These MSA's from east to west include the Pittsfield, MA MSA (84,699 residents plus 50,254 residents of Berkshire county, MA who reside outside the MSA), the Albany–Schenectady–Troy, NY MSA (875,583 residents), the Glens Falls, NY MSA (124,345 residents), the Utica–Rome, NY MSA (299,896), the Syracuse, NY MSA (732,117 residents), the Rochester, NY MSA (1,098,201 residents), and the Buffalo–Niagra Falls, NY MSA (1,170,111 residents).

The **Scranton–Harrisburg** air quality region (3,407,205 residents) consists a band of six MSA's (24,504 km^2 with 139 residents per km^2) that are located just west of the Philadelphia and New York regions. These MSA's include the Scranton–Wilkes-Barre–Hazleton, PA MSA (624,776 residents), the Allentown–Bethlehem–Easton, PA MSA (637,958 residents), the Reading, PA MSA (373,638 residents), the Harrisburg–Lebanon–Carlisle, PA MSA (629,401 residents), the Lancaster, PA MSA (470,658 residents), and the York, PA MSA (381,751 residents). This region also includes Monroe county, PA (138,687 residents); an isolated, non-MSA county just northeast of the Allentown–Bethlehem–Easton, PA MSA.

The **Pittsburgh to Cleveland** air quality region (7,087,165 residents) consists of a contiguous band of eight MSA's/CMSA's from Pittsburgh, PA to Cleveland, OH (36,562 km^2 with 194 residents per km^2). These MSA's include the Pittsburgh, PA MSA (2,358,695 residents), the Sharon, PA MSA (120,293 residents), the Steubenville–Weirton, OH–WV MSA (132,008 residents), the Wheeling, WV–OH MSA (153,172 residents), the Canton–Massillon, OH MSA (406,934 residents), the Erie, PA MSA (280,843 residents), the Youngstown–Warren, OH MSA (594,746 residents), and the Cleveland–Akron, OH CMSA. The Cleveland–Akron, OH CMSA includes the Akron, OH PMSA (694,960 residents) and the Cleveland–Lorain–Elria, OH PMSA (2,250,871 residents).

The **Toledo–Detroit–Flint** air quality region (6,074,631 residents) consists of the Toledo, OH MSA (618,203 residents) and the Detroit–Ann Arbor–Flint, MI CMSA (20,631 km^2 with 294 residents per km^2). The Detroit–Ann Arbor–Flint, MI CMSA includes the Ann Arbor, MI PMSA (578,736 residents), the Detroit, MI PMSA (4,441,551 residents), and the Flint, MI PMSA (436,141 residents).

The **Milwaukee–Chicago–Gary** air quality region (10,847,112 residents) consists of the Chicago–Gary–Kenosha, IL–IN–WI CMSA and the Milwaukee–Racine, WI CMSA (22,742 km^2 with 477 residents per km^2). The Chicago–Gary–Kenosha, IL–IN–WI CMSA includes the Gary, IN PMSA (631,362 residents), the Chicago, IL PMSA (8,272,768 residents), the Kankakee, IL PMSA (103,833 residents), and the Kenosha, WI PMSA (149,577 residents). The Milwaukee–Racine, WI CMSA includes the Milwaukee–Waukesha, WI PMSA (1,500,741 residents) and the Racine, WI PMSA (188,831 residents).

The **Minneapolis–St. Paul** air quality region (2,968,806 residents) consists of the Minneapolis–St. Paul, MN–WI MSA (16,349 km^2 with 182 residents per km^2).

The **Richmond to Norfolk** air quality region (2,566,053 residents) consists two contiguous MSA's in central Virginia (13,845 km^2 with 185 residents per km^2) including the Richmond–Petersburg, VA MSA (996,512 residents) and the Norfolk–Virginia Beach–Newport News, VA–NC MSA (1,569,541 residents).

The **Raleigh to Greenville** air quality region (4,901,184 residents) consists of a band of four contiguous MSA's running from central North Carolina to the western tip of South Carolina along two interstate corridors (36,347 km^2 with 135 residents per km^2). These four MSA's include the Raleigh–Durham–Chapel Hill, NC MSA (1,187,941 residents), the Greensboro–Winston-Salem–High Point, NC MSA (1,251,509 residents), the Charlotte–Gastonia–Rock Hill, NC–SC MSA (1,499,293 residents), and the Greenville–Spartanburg–Anderson, SC MSA (962,441 residents).

The **Atlanta** air quality region (4,112,198 residents) consists of the Atlanta, GA MSA (15,880 km^2 with 259 residents per km^2).

The **Florida Peninsula** air quality region (14,520,138 residents) consists of 40 counties in the Florida peninsula (96,957 km^2 with 150 residents per km^2). This air quality region includes 13 non-MSA counties in the Florida peninsula south of Gainesville, FL and 15 MSA's: Jacksonville, FL (1,100,491 residents); Gainesville, FL (217,955 residents); Dayton Beach, FL (493,175 residents); Ocala, FL (258,916 residents); Orlando, FL (1,644,561 residents); Melbourne–Titusville–Palm Bay, FL (476,230 residents); Lakeland–Winter Haven, FL (483,924 residents); Tampa–St. Petersburg–Clearwater, FL (2,395,997 residents); Sarasota–Bradenton, FL (589,959 residents); Punta Gorda, FL (141,627 Residents); Fort Myers–Cape Coral, FL (440,888 residents); Naples, FL (251,377 residents); Fort Pierce–Port St. Lucie, FL (319,426 residents); West Palm Beach–Boca Raton, FL (1,131,184 residents); and Miami–Fort Lauderdale, FL (3,876,380 residents).

The **Pensacola to New Orleans** air quality region (3,528,105 residents) consists of a band of five contiguous MSA's running along the Gulf coast from Pensacola, FL to New Orleans, LA (34,896 km^2 with 101 residents per km^2). These MSA's include the Pensacola, FL MSA (412,153 residents), the Mobile, AL MSA (540,258 residents), the Biloxi–Gulfport–Pascagoula, MS MSA (363,988 residents), the Baton Rouge, LA MSA (602,894 residents), and the New Orleans, LA MSA (1,337,726 residents).

The **Houston** air quality region (4,669,571 residents) consists of the Houston–Galveston–Brazoria, TX CMSA (20,201 km^2 with 231 residents per km^2). The Houston–Galveston–Brazoria, TX CMSA includes the Brazoria, TX PMSA (241,767 residents), the Galveston–Texas City, TX PMSA (250,158 residents), and the Houston, TX PMSA (4,177,646 residents).

The **Dallas/Fort Worth** air quality region (5,221,801 residents) consists of the Dallas–Fort Worth, TX CMSA (24,060 km^2 with 217 residents per km^2). The Dallas–Fort Worth, TX CMSA includes the Dallas, TX PMSA (3,519,176 residents) and the Fort Worth–Arlington, TX PMSA (1,702,625 residents).

The **St. Louis** air quality region (2,603,607 residents) consists of the St. Louis, MO–IL MSA (16,733 km^2 with 156 residents per km^2).

The **Front Range (Denver)** air quality region (3,573,008 residents) consists of a band of five contiguous MSA's running just east of the front range of the Rocky Mountains (47,364 km^2 with 75 residents per km^2). These MSA's include the Cheyenne, WY MSA (81,607 residents), the Fort Collins–Loveland, CO MSA (251,494 residents), the Denver–Boulder–Greeley, CO CMSA, the Colorado Springs, CO MSA (516,929 residents), and the Pueblo, CO MSA (141,472 residents). The Denver–Boulder–Greeley, CO CMSA includes the Boulder–Longmont, CO PMSA (291,288 residents), the Denver, CO PMSA (2,109,282 residents), and the Greeley, CO PMSA (180,936 residents).

The **Phoenix–Mesa** air quality region (3,251,876 residents) consists of the Phoenix–Mesa, AZ MSA. The Phoenix–Mesa air quality region includes over 37,212 km^2 (87 residents per km^2) due to the large size of Arizona counties, but most of the population resides in a denser urban core.

The **Los Angeles/San Diego** air quality region (19,187,478 residents) consists of the San Diego, CA MSA (2,813,833 residents) and the Los Angeles–Riverside–Orange County, CA CMSA (98,535 km^2 with 195 residents per km^2). The Los Angeles–Riverside–Orange County, CA CMSA includes the Los Angeles–Long Beach, CA PMSA (9,519,338 residents), the Orange County, CA PMSA (2,846,289 residents), the Riverside–San Bernardino, CA PMSA (3,254,821 residents), and the Ventura, CA PMSA (753,197 residents). The effective population density of this urban region is understated due to the inclusion of two large counties: San Bernardino and Riverside.

The **San Francisco** air quality region (7,039,362 residents) consists of the San Francisco–Oakland–San Jose, CA CMSA (19,058 km^2 with 369 residents per km^2). The San Francisco–Oakland–San Jose, CA CMSA includes the Oakland, CA PMSA (2,392,557 residents), the San Francisco, CA PMSA (1,731,183 residents), the San Jose, CA PMSA (1,682,585 residents), the Santa Cruz–Watsonville, CA PMSA (255,602 residents), the Santa Rosa, CA PMSA (458,614 residents), and the Vallejo–Fairfield–Napa, CA PMSA (518,821 residents).

The **Seattle–Tacoma** air quality region (3,554,760 residents) consists of the Seattle–Tacoma–Bremerton, WA CMSA (18,528 km^2 with 192 residents per km^2). The Seattle–Tacoma–Bremerton, WA CMSA includes the Bremerton, WA PMSA (231,969 residents), the Olympia, WA PMSA (207,355 residents), the Seattle–Bellevue–Everett, WA PMSA (3,554,760 residents), and the Tacoma, WA PMSA (700,820 residents).

Large City Regions

The **Portland** air quality region (2,265,223 residents) consists of the Portland–Salem, OR–WA CMSA (18,153 km^2 with 125 residents per km^2). The Portland–Salem, OR–WA CMSA includes the Portland–Vancouver, OR–WA PMSA (1,918,009 residents) and the Salem, OR PMSA (347,214 residents).

The **Cincinnati** air quality region (1,979,202 residents) consists of the Cincinnati–Hamilton, OH–KY–IN CMSA (9,932 km^2 with 199 residents per km^2). The Cincinnati–Hamilton, OH–KY–IN CMSA consists of the Cincinnati, OH–KY–IN PMSA (1,646,395 residents) and Hamilton–Middletown, OH PMSA (332,807 residents).

The **Sacramento** air quality region (1,796,857 residents) consists of the Sacramento–Yolo, CA MSA (13,488 km^2 with 133 residents per km^2).

The **Kansas City** air quality region (1,776,062 residents) consists of the Kansas City, MO–KS MSA (13,945 km^2 with 127 residents per km^2).

The **Provo–Salt Lake City** air quality region (1,702,450 residents) consists two contiguous MSA's that are located in northern Utah (10,908 km^2 with 156 residents per km^2). These MSA's include the Provo–Orem, UT MSA (368,536 residents) and the Salt Lake City–Ogden, UT MSA (1,333,914 residents).

The **Indianapolis** air quality region (1,607,486 residents) consists of the Indianapolis, IN MSA (9,276 km^2 with 173 residents per km^2).

The **San Antonio** air quality region (1,592,383 residents) consists of the San Antonio, TX MSA (8,607 km^2 with 185 residents per km^2).

The **Las Vegas** air quality region (1,563,282 residents) consists of the Las Vegas, NV–AZ MSA. The Las Vegas air quality region includes over 101,830 km^2 (15 residents per km^2) due to the large size of Nevada counties, but most of the population resides in a denser urban core.

The **Columbus** air quality region (1,540,157 residents) consists of the Columbus, OH MSA (8,211 km^2 with 188 residents per km^2).

The **Austin–San Marcos** air quality region (1,249,763 residents) consists of the Austin–San Marcos, TX MSA (10,999 km^2 with 114 residents per km^2).

The **Nashville** air quality region (1,231,311 residents) consists of the Nashville, TN MSA (10,576 km^2 with 116 residents per km^2).

The **Memphis** air quality region (1,135,614 residents) consists of the Memphis, TN–AR–MS MSA (7,855 km^2 with 145 residents per km^2).

The **Grand Rapids** air quality region (1,088,514 residents) consists of the Grand Rapids–Muskegon–Holland, MI MSA (7,302 km^2 with 149 residents per km^2).

The **Oklahoma City** air quality region (1,083,346 residents) consists of the Oklahoma City, OK MSA (10,998 km^2 with 99 residents per km^2).

The **Louisville** air quality region (1,025,598 residents) consists of the Louisville, KY–IN MSA (5,324 km^2 with 193 residents per km^2).

The **Dayton** air quality region (950,558 residents) consists of the Dayton–Springfield, OH MSA (4,274 km^2 with 222 residents per km^2).

The **Fresno** air quality region (922,516 residents) consists of the Fresno, CA MSA (20,659 km^2 with 45 residents per km^2).

The **Birmingham** air quality region (921,106 residents) consists of the Birmingham, AL MSA (8,198 km^2 with 112 residents per km^2).

The **Tucson** air quality region (843,746 residents) consists of the Tucson, AZ MSA. The Tucson air quality region includes over 23,627 km^2 (36 residents per km^2) due to the large size of Arizona counties, but most of the population resides in a denser urban core.

The **Tulsa** air quality region (803,235 residents) consists of the Tulsa, OK MSA (13,203 km^2 with 61 residents per km^2).

The **El Paso** air quality region (679,622 residents) consists of the El Paso, TX MSA (2,543 km^2 with 267 residents per km^2).

Rural Regions

The **Northern New England** air quality region (2,241,468 residents) consists of 42 counties (149,718 km^2 with 15 residents per km^2) north of the Boston/Providence/Hartford and Albany to Niagra air quality regions. This rural air quality region includes the Bangor, ME MSA (90,864 residents), the Lewiston–Auburn, ME MSA (90,830 residents), and the Burlington, VT MSA (169,391 residents).

The **Northern Appalachia** air quality region (3,588,349 residents) consists of 55 counties (107,402 km^2 with 33 residents per km^2) of the Appalachian Region in New York and Pennsylvania north of the Mason-Dixon line (aside from one rural county in southwestern Pennsylvania). This rural air quality region includes the Jamestown, NY MSA (139,750 residents), the Elmira, NY MSA (91,070 residents), the Binghamton, NY MSA (252,320 residents), the Williamsport, PA MSA (120,044 residents), the State College, PA MSA (135,758 residents), the Johnstown, PA MSA (232,621 residents), and the Altoona, PA MSA (129,144 residents).

The **Central Appalachia** air quality region (2,537,893 residents) consists of 87 counties (98,645 km^2 with 26 residents per km^2) of the Appalachian Region in Ohio and in Maryland, West Virginia and Virginia south of the Mason-Dixon line (aside from one rural county in southwestern Pennsylvania). This rural air quality region includes the Cumberland, MD–WV MSA (102,008 residents) and the Charleston, WV MSA (251,662 residents).

The **South Central Appalachia** air quality region (1,566,683 residents) consists of 71 counties (65,669 km^2 with 24 residents per km^2) of the Appalachian Region in eastern Kentucky and Tennessee. This rural air quality region contains no MSA's.

The **Southeastern Appalachia** air quality region (2,154,049 residents) consists of 54 counties (53,304 km^2 with 40 residents per km^2) of the Appalachian Region in western North Carolina and northern Georgia. This rural air quality region includes the Hickory–Morganton–Lenoir, NC MSA (341,851 residents), the Asheville, NC MSA (225,965 residents), and the Athens, GA MSA (153,444 residents).

The **Bluegrass** air quality region (1,410,263 residents) consists of 41 counties (37,115 km^2 with 38 residents per km^2) in western Kentucky and Tennessee. This rural air quality region includes the Lexington, KY MSA (479,198 residents) and the Clarksville–Hopkinsville, TN–KY MSA (207,033 residents).

The **Piedmont** air quality region (2,093,921 residents) consists of 61 counties (59,493 km^2 with 35 residents per km^2) central Virginia and eastern North Carolina. This rural air quality region includes five MSA's: Charlottesville, VA (159,576 residents); Roanoke, VA (235,932 residents); Lynchburg, VA (214,911 residents); Danville, VA (110,156 residents), and Rocky Mount, NC (143,026 residents).

The **Southeast** air quality region (6,697,074 residents) consists of 171 counties (203,124 km^2 with 33 residents per km^2) from central North Carolina to eastern Alabama. This rural air quality region includes 13 MSA's: Goldsboro, NC (113,329 residents); Fayetteville, NC (302,963 residents); Florence, SC (125,761 residents); Columbia, SC (536,691 residents); Sumter, SC (104,646 residents); Augusta–Aiken, GA–SC (477,441 residents); Athens, GA (153,444 residents); Macon, GA (322,549 residents); Albany, GA (120,822 residents); Columbus, GA–AL (274,624 residents); Auburn–Opelika, AL (115,092 residents); and Dothan, AL (137,916 residents).

The **South Central** air quality region (4,419,205 residents) consists of 127 counties (205,746 km^2 with 22 residents per km^2) in western Alabama and Tennessee and eastern Mississippi. This rural air quality region includes 6 MSA's: Gadsden, AL (103,459 residents); Anniston, AL (112,249 residents); Montgomery, AL (333,055 residents); Tuscaloosa, AL (164,875 residents); Jackson, MS (440,801 residents); Hattiesburg, MS (111,674 residents); and Jackson, TN (107,377 residents).

The **West South Central** air quality region (2,723,327 residents) consists of 71 counties (141,131 km^2 with 19 residents per km^2) in northwestern Louisiana, eastern Texas and southwest Arkansas. This rural air quality region includes six MSA's: Alexandria, LA (126,337 residents); Monroe, LA (147,250 residents); Shreveport–Bossier City, LA (392,302 residents); Texarkana, TX–Texarkana, AR (129,749 residents); Longview–Marshall, TX (208,780 residents); and Tyler, TX (174,706 residents).

The **Eastern Mid-West** air quality region (6,486,226 residents) consists of 114 counties (128,926 km^2 with 50 residents per km^2) in western Ohio, Indiana, and southern Michigan. This semi-rural air quality region includes 15 MSA's: Mansfield, OH (175,818 residents); Lima, OH (155,084 residents); Jackson, MI (158,422 residents); Lansing–East Lansing, MI (447,728 residents); Kalamazoo–Battle Creek, MI (452,851 residents); Benton Harbor, MI (162,453 residents); South Bend, IN (265,559 residents); Fort Wayne, IN (502,141 residents); Elkhart–Goshen, IN (182,791 residents); Muncie, IN (118,769 residents); Kokomo, IN (101,541 residents); Lafayette, IN (182,821 residents); Terre Haute, IN (149,192 residents); and Bloomington, IN (120,563 residents).

The **Central Mid-West** air quality region (11,927,428 residents) consists of 363 counties (569,631 km^2 with 21 residents per km^2) in Illinois, southern Wisconsin, Iowa, Missouri, northern

Arkansas, and eastern Kansas and Nebraska. This rural air quality region includes 22 MSA's: Champaign–Urbana, IL (179,669 residents); Decatur, IL (114,706 residents): Bloomington–Normal, IL (150,433 residents); Peoria–Perkin, IL (347,387 residents); Springfield, IL (201,437 residents); Davenport–Moline–Rock Island, IA–IL (359,062 residents); Rockford, IL (371,236 residents); Janesville–Beloit, WI (152,307 residents); Madison, WI (426,526 residents); Dubuque, IA (89,143 residents); Cedar Rapids, IA (191,701 residents); Iowa City, IA (111,006 residents); Waterloo–Cedar Falls, IA (128,012 residents); Des Moines, IA (456,022 residents); Sioux City, IA–NE (124,130 residents); Omaha, NE–IA (716,998 residents) Lincoln, NE (250,291 residents); St. Joseph, MO (102,490 residents); Columbia, MO (135,454 residents); Wichita, KS (545,220 residents); Topeka, KS (169,871 residents); Lawrence, KS (99,962 residents); and Jonesboro, AR (82,148 residents).

The **North Michigan** air quality region (1,458,632 residents) consists of 39 counties (58,549 km^2 with 25 residents per km^2) in Michigan north of a line between Grand Rapids and Flint. This rural air quality region includes the Saginaw–Bay City–Midland, MI MSA (403,070 residents).

The **Upper Mid-West** air quality region (5,549,381 residents) consists of 178 counties (422,834 km^2 with 13 residents per km^2) in the Michigan peninsula, northern Wisconsin and Iowa, Minnesota, and the eastern edges of North and South Dakota along the Red River. This rural air quality region includes 12 MSA's: Sheboygan, WI (112,646 residents); Green Bay, WI (226,778 residents); Appleton–Oshkosh–Neenah, WI (358,365 residents); Wausau, WI (125,834 residents); Eau Claire, WI (148,337 residents); La Crosse, WI (126,838 residents); Rochester, MN (124,277 residents); St. Cloud, MN (167,392 residents); Duluth–Superior, MN–WI (243,815 residents); Grand Forks, ND–MN (97,478 residents); Fargo–Moorhead, ND–MN (174,367 residents) and Sioux Falls, SD (172,412 residents).

The **Central Texas / Oklahoma** air quality region (2,212,566 residents) consists of 71 counties (151,668 km^2 with 15 residents per km^2) in central Oklahoma and Texas. This rural air quality region includes five MSA's: Enid, OK (57,813 residents); Waco, TX (213,517 residents); Killeen–Temple, TX 312,952 residents); Sherman–Denison, TX (110,595 residents); and Bryan–College Station, TX (152,415 residents).

The **Ozark Plateau** air quality region (2,404,760 residents) consists of 65 counties (124,454 km^2 with 19 residents per km^2) in northwestern Arkansas, eastern Oklahoma, and southwestern Missouri. This rural air quality region includes 4 MSA's: Fort Smith, AR–OK (207,290 residents); Fayetteville–Springdale–Rogers, AR (311,121 residents); Joplin, MO (157,322 residents); and Springfield, MO (325,721 residents).

The **California Central Valley** air quality region (3,226,466 residents) consists of 24 counties (96,804 km^2 with 33 residents per km^2) in the central valley of California. This rural air quality region includes six MSA's: Bakersfield, CA (661,645 residents); Visalia–Tulare–Porterville, CA (368,021 residents); Merced, CA (210,554 residents); Modesto, CA (446,997 residents); Stockton–Lodi, CA (563,598 residents); Yuba City, CA (139,149 residents); Chico–Paradise, CA (203,171 residents); and Redding, CA (163,256 residents).

The **Columbia Plateau** air quality region (1,060,554 residents) consists of 17 counties (61,251 km^2 with 17 residents per km^2) in western Washington. This rural air quality region includes the Spokane, WA MSA (417,939 residents) and the Richland–Kennewick–Pasco, WA MSA (191,822 residents).

Valley Regions

The **Ohio Valley** air quality region (1,500,130 residents) consists of the 45 counties (41,769 km^2 with 36 residents per km^2) along the Ohio River Valley from the Steubenville, OH MSA to the Mississippi River. This region includes the Parkersburg–Marietta, WV–OH MSA (151,237 residents), the Huntington–Ashland, WV–KY–OH MSA (315,538 residents), the Evansville–Henderson, IN–KY MSA (296,195 residents) and the Owensboro, KY MSA (91,545 residents), but does not include the Cincinnati, OH, MSA or the Louisville, KY–IN MSA.

The **Upper Tennessee Valley** air quality region (1,846,978 residents) consists of 25 counties (23,363 km^2 with 79 residents per km^2) in eastern Tennessee and southwestern Virginia along the Tennessee River. This region includes the Johnson City–Kingsport–Bristol, TN–VA MSA (480,091 residents), the Knoxville, TN MSA (687,249 residents), and the Chattanooga, TN–GA MSA (465,161 residents).

The **Lower Tennessee Valley** air quality region (1,002,471 residents) consists of 21 counties (29,193 km^2 with 34 residents per km^2) in Alabama and western Tennessee along the Tennessee River. This region includes the Huntsville, AL MSA (342,376 residents), the Decatur, AL MSA (145,867 residents), and the Florence, AL MSA (142,950 residents).

The **Lower Mississippi Valley** air quality region (1,733,195 residents) consists of 54 counties (78,284 km^2 with 22 residents per km^2) from southern Illinois and Missouri to the Gulf of Mexico along the Mississippi River and a portion of the lower Red River in Arkansas. This region includes the Little

Rock–North Little Rock, AR MSA (583,845 residents) and the Pine Bluff, AR MSA (84,278 residents), but does not include the Memphis, TN–AR–MS MSA or the Lafayette, LA MSA.

Coastal Regions

The **Mid-Atlantic Coast** air quality region (801,504 residents) consists of 21 counties (18,776 km^2 with 43 residents per km^2) in eastern Virginia and on the DelMarVa peninsula that are bounded by the Richmond–Petersburg, VA MSA, the Washington–Baltimore, DC–MD–VA–WV CMSA, and the Philadelphia–Wilmington–Atlantic City, PA–NJ–DE–MD CMSA. This region includes the Dover, DE MSA (126,697 residents).

The **Southeast Coast** air quality region (2,770,723 residents) consists of 48 counties (71,641 km^2 with 39 residents per km^2) along the Atlantic coast from North Carolina to Georgia. This region includes the Greenville, NC MSA (133,798 residents), the Jacksonville, NC MSA (150,355 residents), the Wilmington, NC MSA (233,450 residents), the Myrtle Beach, SC MSA (196,629 residents), the Charleston–North Charleston, SC MSA (549,033 residents), and the Savannah, GA MSA (293,000 residents).

The **East Gulf Coast** air quality region (713,116 residents) consists of 18 counties (31,225 km^2 with 23 residents per km^2) along the Gulf coast in the Florida panhandle. This region includes the Tallahassee, FL MSA (284,539 residents), the Panama City, FL MSA (148,217 residents), and the Fort Walton Beach, FL MSA (170,498 residents).

The **Central Gulf Coast** air quality region (1,481,780 residents) consists of 19 counties (40,488 km^2 with 37 residents per km^2) along the Gulf coast from the New Orleans to the Houston. This region includes the Houma, LA MSA (194,477 residents), the Lafayette, LA MSA (385,647 residents), the Lake Charles, LA MSA (183,577 residents), and the Beaumont–Port Arthur, TX MSA (385,090 residents), but does not include the Houston–Galveston–Brazoria, TX MSA or the New Orleans, LA MSA.

The **Western Gulf Coast** air quality region (996,651 residents) consists of 13 counties (28,138 km^2 with 35 residents per km^2) along the Gulf coast of Texas from Houston to the Mexican border. This region includes the Victoria, TX MSA (84,088 residents), the Corpus Christi, TX MSA (380,783 residents), and the Brownsville–Harlingen–San Benito, TX MSA (335,227 residents).

The **California Coast** air quality region (1,101,024 residents) consists of 4 counties (27,653 km^2 with 40 residents per km^2) along the Pacific coast of southern California. This region includes the Salinas, CA MSA (401,762 residents), the San Luis Obispo–Atascadero–Paso Robles, CA MSA (246,681 residents), and the Santa Barbara–Santa Maria–Lompoc, CA MSA (399,347 residents).

The **North Pacific Coast** air quality region (2,056,047 residents) consists of 28 counties (128,492 km^2 with 16 residents per km^2) along the Pacific coast from the Canadian border to northern California. This region includes the Bellingham, WA MSA (166,814 residents), the Corvallis, OR MSA (78,153 residents), the Medford–Ashland, OR MSA (181,269 residents), and the Eugene–Springfield, OR MSA (322,959 residents).

Extremely Low-density Regions

The **High Plains** air quality region (2,021,475 residents) consists of 223 counties (858,648 km^2 with 2.4 residents per km^2) east of the Rocky Mountains from southern Colorado to the Canadian Border. This region includes the Billings, MT MSA (129,352 residents), the Casper, WY MSA (66,533 residents), the Rapid City, SD MSA (88,565 residents), and the Bismark, ND MSA (94,719 residents).

The **Great Plains** air quality region (2,070,401 residents) consists of 126 counties (381,355 km^2 with 5.4 residents per km^2) in northern Texas, eastern Oklahoma, southwest Kansas, southeastern Colorado, and northeastern New Mexico. This region includes the Abilene, TX MSA (126,555 residents), the Amarillo, TX MSA (217,858 residents), the Lubbock, TX MSA (242,628 residents), the Wichita Falls, TX MSA (140,518 residents), and the Lawton, OK MSA (114,996 residents).

The **Southwest** air quality region (4,478,318 residents) consists of 97 counties (687,524 km^2 with 6.5 residents per km^2) from southern Texas, through New Mexico and Arizona, to southern California. This region includes eight MSA's: McAllen–Edinburg–Mission, TX (569,463 residents); Laredo, TX (193,117 residents); San Angelo, TX (104,010 residents); Odessa–Midland, TX (237,132 residents); Las Cruces, NM (174,682 residents); Sante Fe, NM (147,635 residents); Albuquerque, NM (712,738 residents); and Yuma, AZ (160,026 residents).

The **Rocky Mountains** air quality region (2,206,886 residents) consists of 118 counties (717,574 km^2 with 3.1 residents per km^2) along the Rocky Mountains from southern Colorado to the Canadian Border. This region includes the Grand Junction, CO MSA (116,255 residents), the Pocatello, ID MSA (75,565 residents), the Missoula, MT MSA (95,802 residents), and the Great Falls, MT MSA (80,357 residents).

The **Great Basin** air quality region (1,235,556 residents) consists of 43 counties (457,727 km^2 with 2.7 residents per km^2) from northern Arizona through eastern Nevada and western Utah into southwestern Idaho and western Oregon. This region includes the Flagstaff, AZ–UT MSA (122,366 residents) and the Boise City, ID MSA (432,345 residents).

The **Coastal Range** air quality region (1,280,350 residents) consists of the 31 counties (257,711 km^2 with 5.0 residents per km^2) from California to Washington along the Sierra Nevada, Coastal and Cascade mountain ranges. This region includes the Reno, NV MSA (339,486 residents) and the Yakima, WA MSA (222,581 residents).